SEDIMENTOLOGICAL AND STRATIGRAPHIC STUDIES OF THE CAMBRO-ORDOVICIAN SUCCESSION IN NORTHWEST SAUDI ARABIA

BY

ABDULLAH MOHAMMEDFAIZ WAHBI

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SEDIMENTOLOGICAL AND STRATIGRAPHIC STUDIES OF THE CAMBRO-ORDOVICIAN SUCCESSION IN NORTHWEST SAUDI ARABIA

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This thesis, written by Abdullah Mohammedfaiz Wahbi under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOLOGY.**

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Dedication

This work is dedicated to the geosciences community

in the Kingdom of Saudi Arabia

ACKNOWLEDGMENTS

I would like to express my sincere acknowledgements to the Department of Earth Sciences at King Fahd University of Petroleum and Minerals. My grateful salutations are owed to my thesis committee members; Dr. Khalid Al-Ramadan, Dr. John Melvin (Saudi Aramco), and Dr. Ahmet Umran Dogan for their guidance and support throughout this expedition. My gratitude is due to the department's chairman; Dr. Abdulaziz Al-Shaibani, respected faculty members and colleagues for their collaboration and encouragement throughout the graduate degree program.

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ABSTRACT

Full Name : [Abdullah Mohammedfaiz Wahbi]

Thesis Title : [Sedimentological and Stratigraphic Studies of the Cambro-Ordovician Succession in Northwest Saudi Arabia]

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In the first field study since 1963, the Cambro-Ordovician clastic succession studied in two areas in northwest Saudi Arabia is interpreted to represent two major lithostratigraphic units based on the integration of sedimentological descriptions, facies associations, facies distributions, petrographic analysis and paleocurrent direction analysis. Including the Siq Sandstone, Quweira Sandstone and parts of the Saq Sandstone, the depositional setting in the Al Ula area is dominated by high-energy, braided-fluvial, in-channel deposition with minor tidal influence. The depositional setting of these sandstone units in the Tabuk area is very similar, but significantly shows an increased tidal dominance with respect to fluvial facies when compared with the succession in the Al Ula area. Variations in facies associations and distributions between the two localities demonstrate evidence of paleogeographic and proximality implications within the overall fluvio-estuarine depositional setting. These facies associations and distributions indicate a major stratigraphic break at the base of the Upper Siq Sandstone, marked by a rejuvenation of fluvial facies. Thin section analysis indicates a petrographic break at the same boundary, marked by the complete loss of feldspars above that level. Paleocurrent directions show a major shift in flow direction, generally from NW to NE, at the same boundary. These observations suggest the need for revisiting the stratigraphic nomenclature and the definition for these sandstone units. The overall recognized

characteristics of these rocks give a strong suggestion of the possible significant role of tectonic fluctuations during the Cambro-Ordovician time, but this needs further work.

ملخص الرسالة

الاسم الكامل: عبدالله محمدفايز عبدالله وهبي

عنوان الرسالة: دراسة الرسوبية والطبقية في التتابع الكامبرو-أوردوفيشي في شمال غرب المملكة العربية السعودية

التخصص: جيولوجيا

تاريخ الدرجة العلمية: مايو 2014

في دراسة حقلية هي الأولى من نوعها منذ عام 1963م ، تُبيّن دراسة التتابع الكامبرو-أوردوفيشي الفُتاتي في منطقتي عمل اختيرت في شمال غرب المملكة العربية السعودية بأنه يشمل وحدتين صخرو-طِباقيّتين ، بناءً على مقارنة ودمج خلاصة الدراسات التالية: وصف الرسوبيات والسحن ، ترابط السحن ، توزيع السحن ، الدراسات الصخرو-مجهرية ، وتحليل اتجاه التيارات القديمة. هذا التتابع يشمل كل من الأحجار الرملية للسِق ، القويرة ، وأجزاء من الحجر الرملي للساق، حيث يُهيمن الترسيب العالي الطاقة ،القاع-جَدولي النهري المُجدَّل على الترسيب الفُتاتي في مقاطع منطقة الدراسة قُرب مدينة العُلا ، مع ملاحظة التأثير الثانوي للترسيب المد-جزري. يتشابه الترسيب النهري في هذا التتابع في منطقة الدراسة في منطقة تبوك ، مع ازدياد ملحوظ لتأثير الترسيب المد-جزري مقارنةً بمنطقة الدراسة قُرب مدينة العُلا. تُظهِر الإختلافات في ترابط وتوزيع السحن في كلتا المنطقتين في هذه الدراسة أدلة على اختلاف الطبيعة الجغرافية الفانية وطبيعة دُنوّ مصدر الترسيب في بيئة الترسيب الخور-نهرية. يُشير ترابط وتوزيع السحن في كلتا المنطقتين على وجود فاصل طِباقي فريد على قاعدة الحجر الرملي للسِق العُلوي، موضَّحاً بتجدد فريد لظهور السحن النهرية. كما تُظهر الدراسات فاصلاً صخرو-مجهري على نفس الحد ، مُبيّناً بالفُقدان التام لمعادن الفِلدسبار لما هو فوق هذا المستوى. في حين تُبيّن دراسة اتجاه التيارات القديمة تغيراً ملحوظاً في إتجاه الجريان ، من الشمال الغربي إلى الشمال الشرقي على نفس المستوى الطَبقي بشكل عام. تُشير مجمل هذه المشاهدات إلى ضرورة إعادة النظر في المُسمّيات الطَبقية والحاجة إلى إعادة تعريف الوحدات الفُتاتية في هذا التتابع. مُجمل الإيضاحات للخصائص المدروسة في هذا العمل تُعطي إيحائات صريحة لإمكانية وجود تقلّبات بِنائية في الفترة الكامبرو-أوردوفيشية في هذه المنطقة ، ما يتطلب المزيد من البحث.

CHAPTER 1

INTRODUCTION

The Cambro-Ordovician clastic succession in the Al Ula area (Figure 3.2, P. 60, and Figure 3.3, P. 61) sits unconformably over a peneplaned surface of the Precambrian basement (Figure 1.1). Juxtaposed to this contact with basement rocks, it is also found to be overlying Precambrian to Early Cambrian sedimentary and metasedimentary deposits, recognized as Jibalah Group in an angular unconformity (Figure 1.2). Studied succession in the Al Ula area includes the Siq and Quweira Sandstones and limited parts of the Saq Sandstone. The Siq Sandstone is informally divided into three units, namely the Lower, Middle and Upper Siq Sandstones. The panoramic photograph in Figure 1.3, taken from the “highpoint” on top of Harrat (lava plain or volcanic field of) Al Uwayrid west of Al Ula, displays most of the succession in the area. The Saq Sandstone crops out further north (Figure 3.3, P. 61).

The Cambro-Ordovician clastic succession in the Tabuk area (Figure 3.4, P. 62) is found at an unconformable peneplaned contact with the Precambrian basement (Figure 1.4). This was investigated as a second study area to the Al Ula to establish any lithostratigraphic and paleogeographic-depositional variations. This composite section covers the Upper Siq Sandstone (see section 4.3.2.2, P. 192), most of the Quweira Sandstones and the basal contact of Saq Sandstone.

Figure 1.1: The Siq Sandstone in an unconformable, peneplaned contact with the Precambrian basement in the Al Ula area; south to area U1.

Figure 1.2: The Jibalah Group found at an angular unconformity (fault?) with the Siq Sandstone in the Al Ula area; south to area U1.

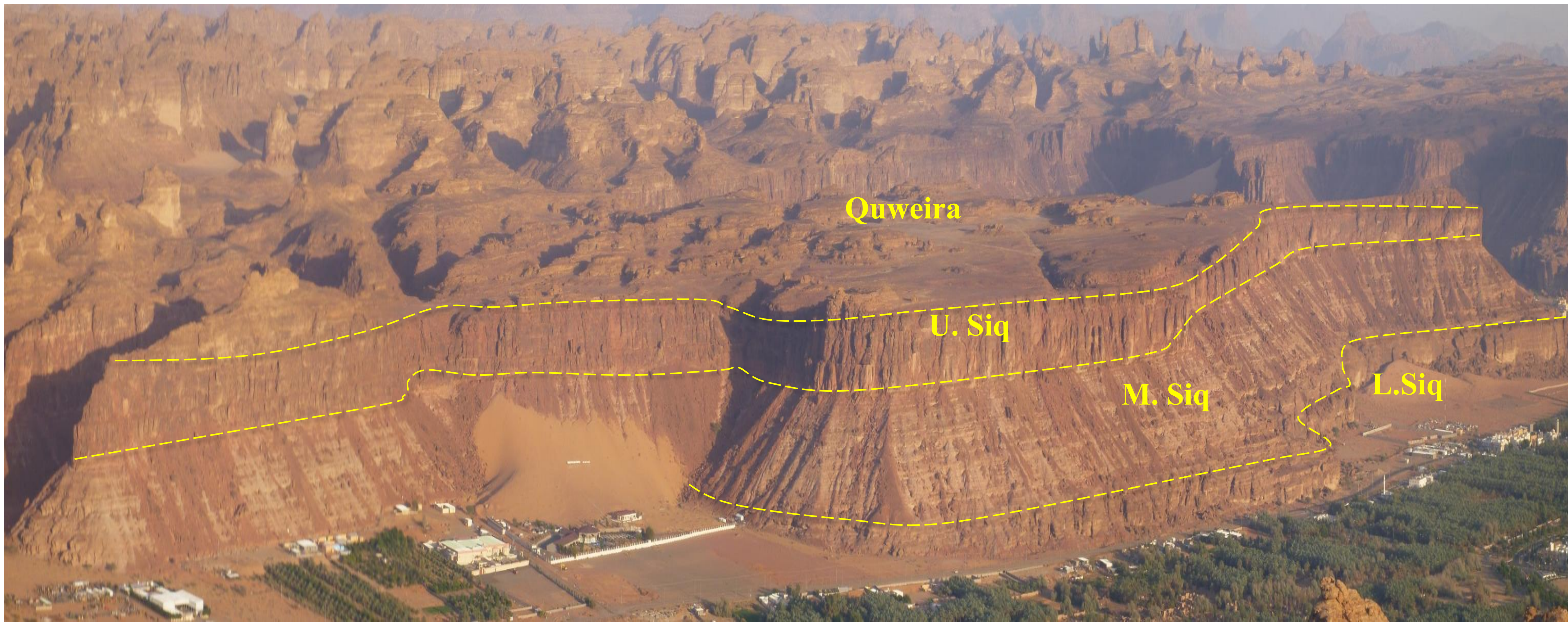


Figure 1.3: Panoramic view (slightly vertically-exaggerated) of most parts of the studied clastic succession in the Al Ula area, taken from the highpoint of Harrat Al Uwayrid, west of the town of Al Ula. This view coincides with the studied line of section U1. Sandstone units are recognized in this section, except for the Saq Sandstone, which crops out further north of this area.

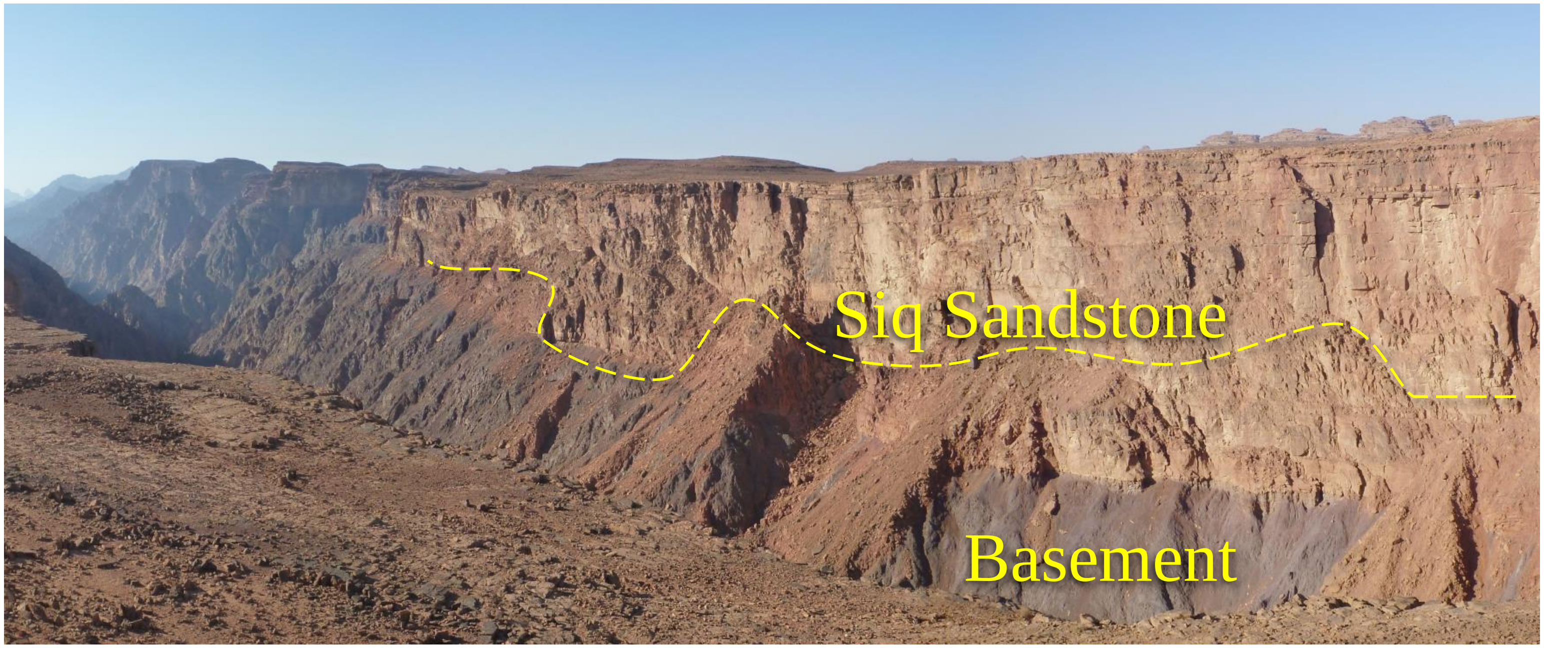


Figure 1.4: Unconformable, peneplaned contact between the Precambrian basement and the Upper Siq Sandstone at Ash' Shiq in the Tabuk area.

CHAPTER 2

LITERATURE REVIEW

Previous work that involved the Cambro-Ordovician succession reveals a great number of different interpretations and speculations that were generally not supported by subjective field studies. Involving different parts of Arabia and Jordan, many interpretations of the depositional environment in northwest Saudi Arabia were based on limited field work and work done elsewhere, most of which was in the interest of geological mapping. This chapter demonstrates the history of previous work on this succession in the northwest Arabian basin, in addition to other different basins. This comprehensive overview demonstrates previous interpretations related to depositional setting, age, paleogeography and depositional environment of this sedimentary succession of Early Paleozoic age.

Table 2.1 introduces a summary of the major stratigraphic units identified in this succession, correlations between the different stratigraphic units in the different localities and the identified ages of each unit according to previous work.

Table 2.1: Summary of stratigraphic identification and correlation between the different Cambro-Ordovician sedimentary units in different localities, in addition to age assignment (modified after Janjou et al., 1996).

<table>
<tr><th rowspan="2">Age (?)</th><th>S. Jordan</th><th colspan="9">Northwest Saudi Arabia</th><th colspan="3">Central Saudi Arabia</th></tr>
<tr><th>Quennell, (1951), Burdon, (1959)</th><th>Bramkamp et al., (1963)</th><th>Powers, (1968)</th><th colspan="2">Al-Laboun, (1986)</th><th colspan="2">Tabuk Quadrangle - Janjou et al., (1996)</th><th colspan="2">Tayma Quadrangle - Vaslet et al., (1994)</th><th>Helal, (1968)</th><th>Powers et al., (1966)</th><th colspan="2">Vaslet et al., (1987)</th></tr>
<tr><td rowspan="2">Early Ordovician</td><td>Umm Sahm Sst.</td><td rowspan="2">Ram and Umm Sahm Sst. (Undiv.)</td><td rowspan="2">Ram and Umm Sahm Sst. (Undiv.)</td><td rowspan="9">Saq Sst.</td><td rowspan="2">Ram and Umm Sahm Sst. (Undiv.)</td><td rowspan="2">Saq Sst.</td><td>Sajir Mb.</td><td rowspan="3">Saq Sst.</td><td rowspan="2">Sajir mb.</td><td rowspan="2">Cruziana Series</td><td rowspan="3">Saq Sst.</td><td rowspan="3">Saq Sst.</td><td rowspan="2">Sajir mb.</td></tr>
<tr><td>Ram Sst.</td><td>Risha Mb.</td></tr>
<tr><td rowspan="3">Late Cambrian.</td><td rowspan="3">Upper Quweira Sst.</td><td rowspan="6">Quweira Sst.</td><td rowspan="6">Quweira Sst.</td><td rowspan="6">Quweira Sst.</td><td colspan="2" rowspan="4">Quweira Sst.</td><td>Risha mb</td><td rowspan="7">Saq Fm.</td><td>Risha mb.</td></tr>
<tr><td colspan="2" rowspan="5">Quweira Sst.</td><td rowspan="5">Quweira Sst.</td><td colspan="2">Yatib Fm.</td></tr>
<tr><td colspan="2" rowspan="5">?</td></tr>
<tr><td rowspan="2">Middle Cambrian.</td><td rowspan="2">Burj Lst. Gr.</td></tr>
<tr><td colspan="2" rowspan="3">Siq Sst.</td></tr>
<tr><td rowspan="2">Early Cambrian.</td><td>Lower Quweira Sst.</td></tr>
<tr><td>Bedded arkosic Sst.</td><td>Siq Sst.</td><td>Siq Sst.</td><td>Siq Sst.</td><td colspan="2">Siq Sst.</td><td>Siq Sst.</td></tr>
<tr><td colspan="14">Proterozoic Basement</td></tr>
</table>

2.1 Stratigraphic Overview from Previous Work

Deposition of Early Paleozoic strata in northern Gondwana regionally covered different basins and locations other than basins found in northwest Arabia, the area of interest in this thesis study. Different studies of Cambro-Ordovician deposits took place in Jordan, different parts of central Arabia, southern Arabia and other locations enclosed. These earlier studies influenced later studies of similar-equivalent rocks in Arabia. In this section, a historical overview will introduce the evolution of the stratigraphic understanding of this succession, and how different interpretations of stratigraphic relations were assessed in the Cambro-Ordovician succession.

2.1.1 Jordan

The early studies of the Nubian Facies (Russegger, 1846-1849) was defined in the northern part of the African-Arabian Continent of Gondwana to loosely refer to different parts of the Precambrian and Middle Cenomanian (Cretaceous) succession (Hull, 1886; Blanckenhorn, 1914; Blake & Ionides, 1939). These observations paved the way for the first comprehensive study of the Cambro-Ordovician clastic succession in Jordan (Quennell, 1951), which replaced the Nubian Facies with Four stratigraphic units: the Quweira Series, the Ram, Umm Sahm and Kurnub Sandstones, older to younger respectively. The Quweira Series includes the Lower Quweira Sandstone, the Burj Limestone Group and the Upper Quweira Sandstone. Bender (1975) divided parts of the same succession into six stratigraphic units. These studies are possibly outdated when it comes to the current stratigraphy in Jordan, but they serve the purpose of the study of this thesis.

2.1.2 The Great Arabian Basin

The Paleozoic sedimentary succession varies significantly between different localities within Saudi Arabia. The main three basins that contain such successions are located in central, northwestern and southern Arabia. These three basins break down further into different study areas and localities. A comprehensive summary will demonstrate the different studies conducted in chronological orders with an emphasis on locations where data and interpretations were conducted.

2.1.2.1 Central Arabia

The first introduction of the Saq Sandstone in Saudi Arabia is gathered in the collective work of Steineke et al. (1958). This unit was reinstated by Powers et al. (1966), and was later formalized in Power's lexicon of Saudi Arabia (Powers, 1968). The Saq Sandstone, introduced by Burchfiel, H. L. and Hoover, J. W. in 1935 (Thralls & Hasson, 1956) and was formalized later into a formation by Bramkamp, R. A. (Steineke et al., 1958), was referenced at Jabal (mount) Saq, west of Unaizah and southeast of Ha'il, and Jabal Al Hanadir, west of Ha'il and east of Tayma, in central Arabia (Powers et al., 1966; Powers, 1968). This unit is alleged to be equivalent to the Siq, Quweira, Ram and Umm Sahm Sandstones in northwestern Arabia. Steineke states that the Saq Sandstone in central Arabia is likely to include Quennell's Quweira, Ram and Umm Sahm Sandstones in Jordan.

The collective work of Vaslet (1987) describes in detail the Paleozoic (pre-Late Permian) in central Arabia. Introducing the Tayma Group, it is proposed to include all pre-glacial Paleozoic lithostratigraphic units in the northern half of Saudi Arabia (Vaslet, 1987, p. 90). The summary the lithostratigraphic correlation between central Arabia, northwestern Arabia and Jordan (Vaslet, 1987, p. 93) is proposed. Basal conglomeratic formation is found in the three regions. It is regarded as the Yatib Formation in Ha'il, the Siq Sandstone near Sha'ib As' Siq in Tabuk region, northwestern Arabia (Bramkamp et al., 1963), and conglomerates at the base of the Quweira Sandstone in the Wadi Al Arabah region in Jordan. The detrital sandstone formation of the Saq Sandstone can be divided into two units. The Risha member is correlatable with the Quweira Sandstone in northwestern Arabia and the Quweira Series in Jordan (Vaslet, 1987). The Sajir member is possibly equivalent to the Ram and Umm Sahm Sandstones, sensu Powers (1968) and the *Cruziana* Series, sensu Helal (1964; 1965; 1968) in northwestern Arabia.

2.1.2.2 Northwestern Arabia

The Siq Sandstone in northwest Arabia was first described by Bramkamp et al. (1963) in Sha'ib as' Siq, recognized as the basal unit in the sedimentary succession. For the remaining sandstone units: the Quweira, Ram and Umm Sahm Sandstones, the original type locality in Jordan was kept to reference outcrops in northwestern Saudi Arabia because it was not possible for these units to be separated by photogeologic interpretations (Bramkamp et al., 1963). However, they were arguably convenient enough to trace to Arabia (Powers et al., 1966).

The Siq Sandstone, the lowermost unit of the Saq Sandstone, was found unconformably in contact with the Jubaylah Group (also Jibalah, J'balah and Jibala Group) in the Mashhad area (Hadley, 1973; 1974; Cloud et al., 1979), found few kilometers south of the Al Ula study area of this thesis.

It is suggested that applying formational names for Early Paleozoic sections from Jordan throughout Saudi Arabia is unrealistic because the Jordan's formations are not well defined lithostratigraphically and local formational nomenclature already exist, creating confusion when overlapping with more broad borrowed names (Helal, 1968). This succession displays diversity of facies and developed stratigraphic sections. They are also distinguished by paleographical and bio-geographical characteristics that vary from Cambrian and Silurian deposits. Central and northwestern Saudi Arabia were inundated by a vast sea, in an epicontinental shelf with shallow-water lithologies of graptolitic shales, siltstones and sandstones. It is also arguably difficult to correlate the Saq Formation with other lithologically-similar rock unites outside central Najd (Arabia) due to lack of faunal evidence (Helal, 1968, p. 521). In an effort to better clarify this succession in Saudi Arabia, more detailed work was done which includes new lithostratigraphic names.

Unlike Powers, Helal (1964; 1965; 1968) confines his Saq Formation to the Cambrian part of the Saq Sandstone in central Arabia, which is laterally equivalent to the Quweira Series in Jordan. In the northwest of Saudi Arabia, the Saq Formation (Helal,

1968) is introduced as the first unit found overlying the Precambrian basement in northern Saudi Arabia. The *Cruziana* Series is introduced (Helal, 1968) comparable to Ram and Umm Sahm Sandstone in Jordan. Quartzite sandstone sheets at the lower part of the Saq Formation in the northwest of Arabia are regarded to be of possible lateral equivalence to the Burj Limestone Group in Jordan (Helal, 1968).

Helal (1968) describes the Cambrian sea to have had transgressed over the Middle East from the northwest, where the Saudi Arabian part was the shelf of the epicontinental sea and the Jabal Saq- Al Uyun area may show the southern-most extension of these deposits, indicated by the presence of carbonates in Jordan and quartizite sheets in the Tabuk area. These Cambrian rocks are not present further south, as the nearest Cambrian rocks are found in southern Persia and southeast Oman. The Saq Formation and its regional equivalent units show no evidence of any orogeny as they lie unconformably flat above different stratigraphic levels of the Precambrian basement complex over a distance of over 800 km.

Later studies estimated the Saq Sandstone in Tabuk and Aqaba, northwest Arabia to comprise five units without precise definition of any (Bigot & Lafoy, 1970). It is also suggested that continental deposition of the Saq Sandstone took place following the Jibalah Group taphrogeosynclinal sediments and the stabilization of the Arabian shield in Tabuk and Widyan Basins in northwest Arabia (Al-Laboun, 1986).

The French Bureau de Recherches Géologiques et Minières (BRGM) field mapping of northwest Saudi Arabia covered a number of exposures of the Cambro-Ordovician succession in the area, assumed here to be fully or partially equivalent to the

Saq Sandstone in central Arabia as indicated by previous work (Helal, 1965; Powers et al., 1966; Glintzboeckel, 1981). In Sahl Al Matran quadrangle (Hadley, 1987), which covers the Al Ula study area of this thesis, the different Quweira, Ram and Umm Sahm sandstone units were lumped because they couldn't be divided photogeologically. It is suggested that the lower contact of the Siq Sandstone in this area is uncertain, and is deposited on a substantially-weathered peneplain paleosurface at or near sea level, observed at no measureable relief at its lower contact (Hadley, 1987). A saprolite zone is observed underlying the Siq Sandstone, consisting of extremely friable country rock (5-10 m thick), with a color derived from parent rock – not commonly oxidized. Non-humid, arid to temperate climatic conditions seem to prevail this period, supported by the absence of laterite, soil or organic remains (Hadley, 1987). The Quweira, Ram and Umm Sahm Sandstones (Undivided), exposed east of the Harrat Al Uwayrid in this area, are considered equivalent to the upper part of the Saq Sandstone of Powers et al. (1966) in central Arabia, with their type localities defined in southern Jordan by Quennell (1951).

The Al Bada' quadrangle report describes the Paleozoic sedimentary rocks cropping out in the eastern part of the mapping area, part of the Hadabat (plateau of) Hisma (Clark, 1986), which covers the Tabuk study area of this thesis study. The east-dipping succession starts with basal conglomeratic deposits of the Siq and Quweira Sandstones at an unconformable contact with the Precambrian basement. This contact is defined by a peneplain surface and a gentle tilt towards the east in this area (Clark, 1986). It is suggested that the westward projection of this peneplain passes just above present summits of the highest mountains of the region ("Exploitation of Sawawin ore deposits," 1981). The Quweira Sandstone shows no fossils in Saudi Arabia, and it conformably overlies the Siq Sandstone. It is also observed to unconformably overlie the Precambrian basement in this area (Clark, 1986). It is overlain by the Ram and Umm Sahm Sandstones. Umm Sahm Sandstone conformably overlies Ram Sandstone.

The Shaghab quadrangle is located between the two study areas of Al Ula and Tabuk in this thesis. The Siq, Quweira, Ram and Umm Sahm Sandstones are persevered in the northern and eastern parts of this mapping area below Cenozoic basaltic lavas of Harrat Ar' Raha and Harrat Uwayrid (Grainger & Hanif, 1989). Early Paleozoic sedimentary rocks overlie the Precambrian basement on a peneplaned surface and underlie Cenozoic lava flow deposits. The western and southern margins of the Paleozoic sandstones and Cenozoic volcanic rocks exposed mark major erosional escarpments displaying numerous mesas, buttes and pinnacles that might be correlatable with Jabal Numran 20 km to the south (Drysdall, 1982), which is indicative of a more extensive sedimentary cover. The Siq Sandstone is found to unconformably overlie Precambrian rocks. The Quweira Sandstone is conformably overlain by Ram and Umm Sahm Sandstone (Undivided).

The Cambro-Ordovician succession in the Tabuk quadrangle (Janjou et al., 1996), located eastward of the Al Bada' quadrangle, includes only the Saq Sandstone, with the Siq and Quweira Sandstones missing. The Saq Sandstone here is regionally interbedded between the Saq and Yatib Sandstones or the Precambrian basement in central Arabia. The Saq Sandstone is divided into the Risha member at the base and the Sajir member at the top, as defined in previous work in central Arabia (Vaslet, 1987). The Quweira Sandstone is found to crop out southwest of the quadrangle in the Hadabat Al Ukhayram area. Marine beds of the Quweira Sandstone are found interbedded between upper continental unit “Massive Brownish Weathered Sandstone” and lower “Arkosic Sandstone” (Bender, 1975) (see section 2.2.1, P. 18). The two lithostratigraphic units of the Saq Sandstone; the Risha and Sajir members are present in this quadrangle. The Risha member outcrops are found in the Jabal Al Mukayman and Jabal Al Kur areas, southwest of mapping area, and the Sajir member outcrops are more concentrated by Wadi Al Jirdahiyah and Wadi Al Fuhah to the northeast (Janjou et al., 1996). The Risha member unconformably overlies the Quweira Sandstone. The Sajir member conformably overlies the Risha member of the Saq Sandstone.

In the Tayma quadrangle, found north of Sahl Al Matran quadrangle, the Early Paleozoic succession is gently dipping towards the north-northeast and is overlain by Mesozoic and Tertiary to Quaternary volcanic and sedimentary rocks (Vaslet et al., 1994). The oldest sedimentary unit cropping out in this area is the Saq Sandstone, divided into the Risha and Sajir members (Vaslet et al., 1985). These two units comprise conglomeratic to silty sandstones laying conformably over the Quweira and Siq Sandstones, cropping out to the south of this quadrangle near Al Ula, where the Siq Sandstone is observed to overlie the Precambrian basement. The Sajir member overlies the Risha at an apparent conformity (Vaslet et al., 1994).

2.1.2.3 Southern Arabia

Previous work by Aramco geologists in Southern Arabia described thick detrital sequence intercalated between the Precambrian basement and the Late Permian Khuff Formation in the Jabal Wajid massif (Vaslet, 1987). The Wajid Sandstone in Southern

Arabia was formalized and identified by these reconnaissance works (Powers et al., 1966; Powers, 1968; Alabouvette & Villemur, 1973), and was divided into the Shum and Ilman members (Greenwood, 1981a; 1981b; Pallister, 1982). Later studies divided this unit into the Ayn, Wajid (sensu) and Bani Khurb Formations ("Geology of exploration work in the Qasim and Wajid Areas," 1984). The Dibsiyah, Sanamah, Khussayyayn and Juwayl members of the Wajid Sandstone were introduced in later studies (Minoux & Janjou, 1986).

2.1.3 Other Areas

The Early Paleozoic succession shows evidence to show elsewhere in north Gondwana (Al-Laboun, 1990). In South Jordan, these deposits are composed of thick siliciclastics of the Cambrian Saleb (excluding the Burj limestone) and Ishrin Formations, The Cambrian-Ordovician Disi Formation, the Ordovician Sahm and Khreim Formations and the Ordovician-Silurian Mudawarah Formation (Selley, 1972). Cambrian conglomerates, sandstones and red beds of the Sadan Formation, sandstones, siltstones and intercalated carbonates of the Koruk (Sosink) Formation, Ordovician siliciclastics of the Bedinan Formation and Upper Ordovician to Devonian siliciclastics of the Handof Formation show a similar succession in southeast Turkey (Rigo de Righi & Cortesini, 1964). Near the Turkish-Iraqi borders – in the Hakkari Province, the succession observed comprises the Lower Cambrian Sadan quartzites, the Middle Cambrian Koruk dolomites and siliciclastics, the Cambrian-Ordovician Seydisehir and the uppermost Ordovician Sort Dere siliciclastics of Ashgillian age (Janvier et al., 1984). Cambrian-Ordovician-

Silurian(?) siliciclastics of the Khabour Quartzite-Shale Formation are exposed in northern Iraq (Buday, 1980). In southwest Iran, outcrops of the siliciclastics Zaigun and Lalun Formations of Cambrian age are found overlain by carbonates and siliciclastics of the Mila and Ilebeyk Formations of the same age, topped by the Ordovician-Silurian siliciclastics Zard Kuh and Gahkum Formations, with variability in this succession with respect to the location (Setudehnia, 1979). The Huqf Group of Late Precambrian is topped by the Lower Cambrian continental siliciclastics of the lower Haima Group in south Oman, with a significant, tectonically-driven, break in between the two towards the southern part of the basin. Northwards, the Late Cambrian to earliest Silurian continental and fossiliferous marine siliciclastics of lower Haima Group, main Haima Group and Misfir Group are exposed (Clarke, 1988). Cambro-Ordovician sandstones and thin Ordovician to Lower Devonian siliciclastics are found in the subsurface Wajid Basin in southwest Arabia (Al-Laboun, 1990). The succession is also represented by thin Wajid Sandstone in Yemen (Geuken, 1966).

2.2 Lithostratigraphic Descriptions and Interpretations

All defined lithostratigraphic and sandstone units are found to be variable when it comes to lithological descriptions and interpreted depositional settings with respect to locality and study. In this section, examples of these variable descriptions and interpretations are presented to allow comparison.

2.2.1 Jordan

The Nubian Facies (Russegger, 1846-1849), which covers all parts of the studied succession, is argued to have been produced under arid conditions, with occasional marine transgressions (Picard, 1938; Sandford, 1944); see also (Vroman, 1944; McKee, 1963; Hinnawi, 1973).

The crystalline basement experienced a number of different tectonic events which produced different types of igneous and metamorphic belts and bodies, as indicated in Jordan in previous work (Quennell, 1951). These were followed by the deposition of terrestrial and occasional marine deposits which might indicate transgressive events. The Saramuj Series can be found overlaying an erosional hiatus of the crystalline basement, separated by later deposits at an angular unconformity (Bender, 1975). As described in previous work, these are well-rounded, well-cemented arkosic and brecciated igneous pebble-size and boulder-size conglomerates with presence of quartz (Blanckenhorn, 1910; 1912; 1914; Fuches, 1915; Blake & Ionides, 1939; Picard, 1941). The term “bedded arkosic sandstone” is identified in localities where the Saramuj conglomerates are missing on a peneplain surface of Precambrian age (Bender, 1975). The later Cambrian Quweira Series can be found directly overlying the Saramuj Series (Lartet, 1869; Hull, 1886; Hull & Kitchener, 1889). This unit is possibly equivalent to the Jibalah Group in the northwest and the Yatib Formation in central Arabia.

The Quweira Series is divided into three members: the Lower Quweira Sandstone, the Burj Limestone Group and the Upper Quweira Sandstone. The Lower Quweira Sandstone is found resting on the Precambrian surface as a series of grits, conglomerates, quartzites and current-bedded sandstones of a predominantly dark red color (Quennell, 1951).The Burj Limestone Group, firstly introduced by Hull (1886), includes limestone, dolomite, shale and marl layers. This group is found missing south of Jordan, including localities such as Petra. One explanation for this is that the marine transgression did not extend that far south (Quennell, 1951). The Upper Quweira Sandstone overlies the Burj Group and is overlain by the Ram Sandstone. It comprises quartzitic and red sandstones and is described in different localities as green, unfossiliferous sandstones and green micaceous shales above black limestones of the Burj Group (Blake & Ionides, 1939).

The overall Quweira Series (Quennell, 1951) is described as white, fine-grained marine-transgressive sandstone beds that inter-fingers, and further south is replaced by the lower-part, brownish-weathering, massive, continental-origin sandstone. This is possibly equivalent to the complete succession in northwest Saudi Arabia (including the Saq Sandstone) (Bender, 1963; 1975).

Overlying the “red” Quweira Sandstones, the summit-forming Ram Sandstone is observed with coarse (but even-grained), loosely-cemented, yellowish sandstone with white weathering (Quennell, 1951). It appears massive with no recognizable bedding. Its distinct lithology can be traced in the area all the way south to Petra, where it is found above the carved facades (Blake & Ionides, 1939). No fossils have been recorded in these deposits. The Ram Sandstone is the top part of the Quweira Series in Quennell’s definition (Quennell, 1951).

The Umm Sahm Sandstone overlies the Quweira Series and it comprises distinctive thick beds in contrast to the Ram Sandstone (Quennell, 1951). These pink, red-purplish weathering varnish colored sandstones feature iron and manganese that might have altered their colors. They have been described to include correlative, fossiliferous dark-colored purple-brown shale and marl beds, yellow-brown sandstones bands and hard purple to brown micaceous sandstone (Blake & Ionides, 1939). Later marine transgression deposits overly the Umm Sahm Sandstone.

Studies done by Bender (1975) produced the succession that starts with; 1) Basal Conglomerate; or with; 2) Bedded Arkosic Sandstones, correlated with the Siq Sandstone in Arabia. Above these continental layers, white, fine-grained intercalated continental-transgressive marine sandstone layers of; 3) Massive Brownish Weathered Sandstone are observed. These sandy marine layers are replaced by dolomite, limestone, and fossiliferous shale of the; 4) Burj Limestone Group (Quennell, 1951; Burdon & Quennell, 1959) in parts of his study area. The previous two sandstone units are equivalent to Quennell's Quweira Sandstone and are correlatable to the Siq and Quweira Sandstones in northwest Saudi Arabia (Powers, 1968). Conformably above the later sandstone units, Bender describes; 5) Massive Whitish Weathered Sandstones, suggested to be correlatable to the Ram and Umm Sahm Sandstone (Undivided) in Saudi Arabia. It is described as coarse-grained, quartz-gravel, cross-bedded sandstone intercalated with micaceous siltite containing *Cruziana*, representative of continental to deltaic-marine sedimentation (Bender, 1975). The uppermost part of these detrital formations in his study is described as; 6) Bedded Brownish Weathered Sandstone, described as medium- to coarse-grained sandstone with trace fossils, indicative of littoral to shallow-marine environment with tidal influences.

Later studies (Selley, 1970; 1972) sedimentologically redefined the Ram and Umm Sahm Sandstones in Jordan into two sedimentary facies, described as; 1) pebbly channel formations (Lloyd, 1968), corresponding to the Ram Sandstone (Disi Formation) and 2) non-pebbly sheet sand, corresponding to the Umm Sahm Sandstone.

2.2.2 The Great Arabian Basin

Different facies descriptions and interpretations were produced from extensive mapping work taking place in Arabia through different times. In this section, a comprehensive description will be presented to allow comparisons.

The Arabian plate and the northern part of the African plate were part of a broad continental shelf margin of Gondwanaland during the Late Precambrian and Paleozoic times (Al-Laboun, 1990). Major intra-continental extension (Berberian & King, 1981; Husseini, 1988) during these times are reflected in conglomeratic, siliciclastics, carbonates and intercalated volcanic deposits of the Jibalah Group (Delfour, 1970) of syn-rift origin accompanying the Najd fault system activity.

The Jibalah Group was interpreted to mark the Proterozoic-Phanerozoic transition (Cloud et al., 1979) and Early Cambrian (Basahal et al., 1984). The northward-bordering Paleo-Tethys Sea invaded the Gondwanaland shelf margin afterwards as an epicontinental sea which allowed the deposition of thick sedimentary succession during the Paleozoic. The first mega-cycle of the Paleozoic is defined by Al-Laboun (1990) to include the Cambrian into Lower Devonian rocks, deposited on a continental stable shelf margin. The Precambrian “sub-Saq” unconformity bounds the basal contact of the first Paleozoic mega-cycle. This cycle starts with continental, non-marine to shallow-marine siliciclastic deposits of the Saq Sandstone, barren of index fossils and age assigned with regards to gross lithology correlation, being bounded by Precambrian and Early Ordovician layers. The Cambrian-age Burj limestone carbonates are found in Jordan northwards. Siliciclastic members of Qasim Formation (Vaslet, 1987) mark the first marine invasion of Arabia, overlying the Saq Sandstone. Two stratigraphic breaks can be recognized within the first mega depositional cycle in Arabia, allowing the subdivision of this sequence into three subcycles (Al-Laboun, 1990). The first lower subcycle is the Cambrian-Ordovician subcycle, marked on the top by regional unconformity related to glaciation and is recognized in the Qasim area (McClure, 1978; Clark-Lowes, 1980; Young, 1981; Vaslet, 1987).

2.2.2.1 Central Arabia

The Saq Sandstone in central Arabia is described as brown to black-weathering, white to buff, massive, commonly cross-bedded, and medium to coarse-grained sandstone (Steineke et al., 1958). It is locally red, with few thin, red, silty members. It unconformably overlies the crystalline basement and underlies shales of basal Tabuk Formation. *Cruziana*-like trace fossils were found in the upper part of this unit with no diagnostic fossils. Described as continental sandstone with thin lenses of purple shale with *Cruziana* trace fossils, Powers explains in his lexicon how the Saq Formation in central Arabia is equivalent to the three sandstone units west of the Nafud in northwest Arabia; the Siq, Quweira and Ram and Umm Sahm (Undivided) Sandstones (Powers, 1968).

The first sedimentary deposition of the Paleozoic succession in the Arabian Platform appears to systematically overlies a major angular unconformity of sedimentary, metamorphic and eruptive rocks known as the Precambrian basement (Vaslet, 1987). This extremely flat contact is probably indicative of a very long period of erosion which caused a peneplanation accompanied by extensive alteration (leaching).

The Yatib Formation is defined in the Ha'il region (Ekren et al., 1987) and is characterized by coarse conglomeratic bodies containing fragments of basement rocks intercalated between the Precambrian basement and the Saq Sandstone (Vaslet, 1987). As these deposits are paleotopographic fills on the Precambrian basement, they represent deposits of Cambrian age. Where the Saq Sandstone directly overlies the Precambrian basement, these deposits occur as discontinuous outcrops with no particular morphologic expression. They are found in an apparent conformity with the base of the Saq Sandstone (Risha member) in places (Vaslet, 1987). The detrital rocks of the Yatib Formation represent a fluviatile domain, where relatively-immature, very-coarse-grained material is indicative of local or relatively nearby sources, perhaps in the basement (Le Strat et al., 1985; Ekren et al., 1987). The finer-grained rocks such as siltite may possibly be attributed to lacustrine environments.

The top of Yatib Formation appears to be channeled by the conglomeratic sandstones containing quartz pebbles (3 cm in diameter) of the Risha member at the base of the Saq Sandstone in central Arabia (Vaslet, 1987). Where the Yatib Formation is missing, an alteration surface, characterized by feldspar kaolinization and oxide and silica migration that preceded deposition of the Saq Sandstone is argued to have marked the peneplain extending over the entire Arabian Peninsula (Drysdall & Bin Abri, 1978).

The Saq Sandstone is divided into two members (Lozej, 1983; Smith, D. C. & Allen, 1984), based on previous BRGM studies in central Arabia (Vaslet et al., 1981; Delfour et al., 1982). A lower member; later called the Risha member, is characterized by coarse- to medium-grained, cross-bedded sandstone containing quartz boulders and rare siltite beds. An upper member; later called the Sajir member, is characterized by a poke of retrograding sequences of medium- to fine-grained, linguoid-rippled, current-rippled and bioturbated (*Cruziana* and *Skolithos* recorded at the top) sandstone and siltite. In the Tayma region, the Saq Sandstone is regarded as retrograding mega-cycles of fluviatile environment to tidal and shallow marine environment transition (Lozej, 1983). Tigillite-bearing sandstone at the top is indicative of subtidal reworking of tidal-flat deposits or abandoned tidal channels. The upper contact is described by Lozej as conformable, which does not necessarily rule out the possibility of a hiatus between the Saq Sandstone and the overlying Tabuk Formation, as defined in previous work (Powers, 1968).

The Saq Formation in Jabal Saq-Al Uyun area in central Najd – Saudi Arabia shows an extensive fossiliferous exposures of *Cruziana* tracks and graptolitic shales in the upper part of the group (Helal, 1968). The excellent exposures between the Khuff escarpment and the basement rocks near Duwadmi consist of highly cross-bedded sandstones, fine conglomerates and sandy sericitic shales in multi-colored beds. Reddish-brown to black iron concretions are common features. There are no signs of alterations and no evidence of contact metamorphism. This exposure led to the subdivision of these Early Paleozoic sediments into well-defined, mappable lithostratigraphic units of the Saq Formation, the *Cruziana* Series and the Tabuk Formation (Helal, 1968).

The Saq Formation is sharply separated by overlying *Cruziana* Series and Didymograptus-Shaly member of the Tabuk Formation, well exposed in Jabal Hanadir and is known as the Hanadir Shale (Helal, 1968). Sandstones and quartz of the Saq Formation are light-grey, buff to reddish brown; weathers to buff to brown; medium- to coarse-grained; friable to moderately-well-cemented, moderately-well-sorted; sub-rounded to rounded; cross-laminated to cross-bedded. Weathering shows wool sack form and creates ridges. The Al Uyun forms the southern-most extend of the Early Paleozoic sea which invaded the Middle East from the northwest. This succession is traceable further north around the Arabian Shield in the Al Ula, Tabuk areas and as far as Jordan (Bender, 1963), a distance of up to 800 km. Being the southern-most extension of the Early Paleozoic, these sediments do not exceed 100 m in thickness in the Jabal Saq and Jabal Hanadir area. The *Cruziana* Series compromises of finer-bedding, current rippled sandstone sandy shale with abundant bioturbation indicative of a littoral environment (Helal, 1968).

Vaslet (1987) suggests that the Saq Sandstone in Jabal Saq is divided into lower Risha member at the base and the Sajir member at the top, named after Wadi Ar' Risha and the village of Sajir (Vaslet et al., 1985), replacing the older nomenclature "lower and upper members" previously applied (Vaslet et al., 1981; Delfour et al., 1982). The Risha member approximately includes the lower half of the Saq Sandstone. It unconformably overlies the Precambrian basement. The Sajir member sandy and silty part of the Saq Sandstone has been preserved by substantial silicification of the top 50 m of Jabal Saq. It is overlain by the Qasim Formation (Llanvirnian to Ashgillian?) in an apparent conformity. The Saq Sandstone shows lateral thickness variations in the southeastward and northwestward directions. Both the Risha and Sajir members are truncated by pre-Khuff Formation erosion paleosurface in the southeast direction, south of Jabal Al Misma (Vaslet, 1987).

Similar rocks to Jabal Saq are also referenced in the Ha’il region to the northeast and Ad’ Dawadimi region to the southeast (Vaslet, 1987). It unconformably overlies the Precambrian basement and shows conglomerate layers. The Saq Sandstone has been described in the Qasim region, between Ha’il and Buraydah, as a sequence of unidirectional cross-bedded sandstone with silty intercalations, displaying bioturbation (*Cruziana* and *Rusophycus*) in the upper part (Clark-Lowes, 1980; Dixon, 1982).

Drill-hole data in the Qasim area also indicates facies evolution from fluviatile environment at the base to a shallow marine environment (Al-Laboun, 1982).

Al Amar fault has no apparent effect on sedimentation of the Saq Sandstone, as thicknesses are similar on both sides of the fault. In the northwest direction, the Risha member transgresses the Yatib Formation in an apparent conformity. Thus, it progressively covers the basement paleorelief that followed the deposition of the Yatib Formation.

Since the publication of Seilacher (1968; 1970), some authors believed that the *Cruziana* may represent a stratigraphic marker on a regional scale, disproved to show any significance and stratigraphic order in central Arabia through vertical logging (Vaslet, 1987). Some of these traces are identified and described in the upper part of the Saq Sandstone in the Qasim region (Powers et al., 1966; Powers, 1968; Clark-Lowes, 1980). Trace fossils at the top of the Risha member form *Cruziana* (Vaslet, 1987), which become very abundant in the clayey-silty layers of the Sajir member. These trace fossils are morphologically comparable to equivalent layers in Jordan (Selley, 1970; 1972). No fragments of trilobite were found to accompany the *Cruziana* anywhere in this region for several square kilometers. Tigillites (*Skolithos*) are found to be constant in diameter and are localized to very abundant vertical burrows attributed to the top of the Sajir member. These vertical burrows are indicative of marine shelf environment. Rare tigillites appear at the top of the Risha member. Weathering due to arid climate causes oxidation and it eliminates preservation of organic-rich material (Vaslet, 1987).

The interpreted paleoenvironment of the Risha member of the Saq Sandstone displays an evolving braided fluviatile sedimentation system in the lower part into transitional marine and deltaic sedimentation in the upper part (Vaslet, 1987). The base of this member irregularly displays relatively-undeveloped conglomerate beds possibly associated with local basement composition (e.g. quartz veins). The first continental facies represent intersecting-braided channels with quartz that is coarse-grained and microconglomeratic at the bottom, but becomes relatively fine-grained and well-sorted at the top. These deposits characterize distal alluvial bodies between one and several meters thick, up to 100 m wide, and several hundred meters long. Upstream fans (alluvial fans and conglomerates) are not present in central Arabia due to erosion or redistribution. The second fluvio-deltaic facies are characterized by more-rectilinear and more-extensive alluvial bodies than those encountered in the basal part of the member, laid by meandering channels. These detrital bodies are better sorted and show graded bedding in places. Inclined bedding, fish-bone structures, and overturned bedding are present in this part of the succession (Vaslet, 1987). *Cruziana* trace fossils occur in pelitic beds at the top of the member and tigillite-bearing sandstone occurs very locally (Vaslet et al., 1985). These fluviatile and fluvio-deltaic facies are present in all outcrops and extend latterly beyond regional realm, as they can be observed in Jordan (Selley, 1970; 1972) as well as the lower part of Wajid Sandstone in Southern Arabia (Dabbagh & Rogers, 1983; Kellogg et al., 1986).

The Sajir member shows evidence of a clear marine influence in prodeltaic shallow-water environment represented in the development of silty facies with more-planer sedimentary structures than the Risha member and more bioturbation (*Cruziana).* Channeling alluvial bodies are still present in the lower part of the member, which become better-sorted and finer-grained in the upper part of the member with evidence of inclined, prograding subhorizontal bodies separated by silty intercalations. These conditions infer a transitional phase into perhaps brackish water or middle-shelf plain marine deposition. Clark-Lowes (1980) described these successions as tidal flats. Shelf conditions are indicated by the presence of tigillites near the top of the Sajir member, as found in the Mazari' Sajir area (Delfour et al., 1982; Vaslet et al., 1985). Meandriform channels are also present in the upper part of the Sajir member elsewhere, suggesting episodes of coastal plain or deltaic maritime deposition. The Sajir member shows prograding beds with local inclinations and overall reworked and diachronic, similar to observations in the Hoggar region in Algeria (Beuf et al., 1971).

Conclusions of his study (Vaslet, 1987, p. 120) suggest that overall pre-glacial Cambro-Ordovician formations (including the Qasim Formation) are predominantly siliciclastic. The Yatib Formation and the lower half of the Saq Sandstone are sandy or even conglomeratic, whereas the upper half of the Saq Sandstone appears to be more siltatic. The Yatib Formation and the lower half of the Saq Sandstone (the Risha member) display bed-on-bed cross bedding, bed-on-bed erosion and channel-on-channel erosion. The upper half of the Saq Sandstone (the Sajir member) is relatively more planar, and it continues to be the same into the Qasim Formation. Thus, this interpretation implies that the sandy Saq Formation corresponds to an epicontinental, not fluviatile, marine environment (Vaslet, 1987). The paleotopography of the Saq Sandstone is associated with the Precambrian basement and the Cambro-Ordovician successions display facies continuity in central Arabia. This association helped suggesting the Tayma Group. While some authors suggested local unconformities between the Saq Sandstone and the Hanadir member of Tabuk Formation (Helal, 1964; Davis et al., 1981), Vaslet (1987) has only observed conformities, although the possible presence of stratigraphic gap is not excluded. Additional work in northwestern Arabia (Tabuk and Tayma) is necessary for a better definition of the Tayma Group.

Subsurface data from the Qasim area show a thinner succession in the lower part of the Saq Sandstone and a thicker succession in the upper part of the Saq Sandstone when compared to the northwest basin. This implies a wedge-like deposition in a continental-marine, littoral environment for the Saq Sandstone (Al-Laboun, 1986).

2.2.2.2 Northwestern Arabia

Resting nonconformably on top of mature, peneplaned igneous and metamorphic basement rocks, the contact between the Jibalah Group rocks and the Saq Sandstone in the northwest Arabia in the Tabuk and Widyan Basins is marked by pebble to boulder conglomerates derived from the basement complex (Powers et al., 1966). However, the contact shows medium- to coarse-grained, cross-bedded rocks of the Saq Sandstone resting on weathered plutonic and metamorphic rocks when observed near both Ar' Ras and Al Idwah in the Qasim area (Al-Laboun, 1986). Absence of boulder conglomerates suggests distance of sedimentary source. This major unconformity marks the Assyntic orogeny in the area (Al-Laboun, 1986).

The Siq Sandstone is interpreted as non-marine sandstone with an unconformable-lower contact with the crystalline basement and an unclear upper contact defined, more likely to be with the Quweira Sandstone in the locality (Bramkamp et al., 1963). The extendable lower contact was able to be traced through Arabia, and was often described as a flat-peneplaned surface, except in places where the Siq Sandstone overlaid a cover of white quartz gravel, found at a steep-dipping conglomeritic contact containing boulders, cobbles and pebbles derived from underlying basement (Powers et al., 1966).

The Quweira Sandstone is reddish-brown, massive to cross-bedded continental sandstone. The Ram and Umm Sahm Sandstones (Undivided) are readily identifiable on aerial photographs and are traced to the type section in Jordan around the margin of the Arabian Shield, where they disappear underneath the Nafud sands towards the east. Although they can be accurately identified apart and mapped separately, they have been mapped undivided for convenience – U.S. Geological Survey Miscellaneous Geologic

Investigations Maps: I-200 a, I-204 A, I-205 A, and I-201 A, all 1963; (Bramkamp et al., 1963). These beds are buff to brown, dark-weathering and cross-bedded. Quartz pebble and granule zones and lenses of purple, sandy shale containing *Cruziana* tracks are common. The lower unit of the Ram Sandstone is light-colored, whitish to buff-weathering, coarse, eolian cross-bedded continental sandstone with common quartz granule and pebble zones. The upper unit of the Umm Sahm Sandstone beds are fluviatile-continental and include trilobite trace fossil beds, which indicates shale lenses were deposited in shallow marine environment.

In Jildiyah, Ha'il (west of central Arabia, east of the Nafud), the Saq Sandstone is found off-white to purple, fine- to medium-grained, poorly indurated, sub-rounded, well-sorted quartz sandstone with streaks of quartz pebbles (Powers et al., 1966). Towards the west near Harrat Al Uwayrid in the Al Ula area, the Ram and Umm Sahm Sandstones show buff, light-grey, red, and brown, weathering to dark-brown and purple, cross-bedded sandstone with common quartz pebble zones and locally interbedded red, ferruginous, sandy shale. Deposits are presumably continental. Thin lenses of purple shale with *Cruziana* indicate marineness in the upper part of the section. The terrane switches from pinnacles and spires (the Ram Sandstone) into cliff-forming eolian cross-bedded sandstone (the Umm Sahm Sandstone) (Powers et al., 1966).

The Saq Sandstone describes the medium- to coarse-grained, red to brown sandstones that are present at Jabal Saq above the basement and below the variegated shales, siltstones and sandstones of the *Cruziana* Series and Tabuk Formation (Helal, 1968). It varies in thickness between Tabuk and Al Ula in the northwest, and the type locality at Jabal Saq (Helal, 1968, p. 515). It also shows an excellent exposure north to the Arabian Shield, overlapping onto the basement with a pronounced unconformity, which preserves a profile of a deeply-weathered desert pediplain. It consists mainly of sandy facies showing brown to black weathering and interbedded silty layers. The sands are medium- to coarse-grained; irregularly sorted with common pebbly bands; massive and cross-bedded. Successive quartzite sheets are common in the lower portion of the formation. The composition suggests marine origin based on the presence of several well-defined extensive quartzite sheets. Direct derivation of sediments from the crystalline basement-terrestrial source origin is unlikely.

The overlying *Cruziana* Series lie conformably, and locally show unconformity, on top of units of the Saq Formation. Apparent unconformity appears at the sharp lithologic contrast between the varicolored Saq Formation and the overlying *Cruziana* Series. Equivalent units were first recorded by Blanckenhorn (1914); see also: (Thralls & Hasson, 1956; Steineke et al., 1958). Similar to units observed below, these outcrops in Saudi Arabia are found in a continuous belt abut the Arabian Shield in central and northwest Arabia. The stratigraphic break at the base of the *Cruziana* Series indicates major facies changes of the Early Paleozoic sedimentary belt. Lack of bottom-dwelling fauna and primary sedimentary structures suggests a deeper-water deposition compared to the underlying Saq Formation (Helal, 1968).

The Early Paleozoic sediments were studied in the area between Al Ula and Tayma with basal conglomerate series that is 10-12 m thick (Helal, 1968). Cambrian sandstones of the Saq Formation here are reddish purple, red, violet, green, greenish-grey and white; range from fine- to coarse-grained, predominantly medium-grained; partially friable; poorly- to well-sorted; medium-bedded; cross-bedded and rippled. Interbedded siltstones are argillaceous; poorly sorted; thinly-bedded and easily eroded. Shales are sandy to silty; very thinly-bedded and micaceous. Thin bands of conglomerates are widely distributed within the sandstone units. They contain pebbles of igneous and metamorphic rocks of the basement. Overlying sediments above (the Tabuk Formation) are at a probable unconformity due to the sharp lithologic contrast with the varicolored Saq Formation and the whitish, massive, weathered sandstones of the Ordovician units, which also includes *Cruziana* tracks (Helal, 1968). A near-shore marine environment is postulated for the Saq Formation based on the lithological character of the sediments. Showing stratigraphic incompleteness and represented by a sharp change in facies compared to the Saq Formation, the Ordovician units arenaceous and argillaceous deposits are identified with *Cruziana* tracks.

In the Tabuk area, the succession abruptly bound against ridges of the Midyan Massif of the Arabian Shield (Helal, 1968). These sandstones are predominantly sandy to sericitic and micaceous. They interfinger graptolitic shales and are interpreted to be epicontinental shallow marine deposits. Similar to Al Uyun and Al Ula areas, they are divided into lithostratigraphic units that include the Saq Formation, *Cruziana* Series and younger units. The Saq Formation disconformably overlies the Precambrian basement with basal conglomerates, probably deposited during an erosional phase that followed the uplift of the Midyan Massif. The upper abrupt contact with the *Cruziana* Series shows both lithological and stratigraphical breaks that represent a depositional hiatus between the two depositional units. The sandstone facies of the Saq Formation show brown to black weathering and interbedded hard silty layers. Where successive sheets of Quartzite are common in the lower part of the formation, the sandstone is generally light-grey to red; medium- to coarse-grained; well-sorted; moderately well-cemented; sub-rounded to rounded; cross-laminated; and thickly cross-bedded. It weathers red to buff cliffs that are latterly equivalent to sandy series in the lower part of section observed in Al Uyun and Al Ula areas. A distinctive feature in this section, however, is the "spore zone" in the lower part of the Saq Formation where abundance of tracks, trails and burrows is observed. Individual burrows reach up to 10 cm in length and several millimeters in diameter in normal, parallel and oblique orientation to the stratification. The *Cruziana* Series and Tabuk Formation above show regular increase in thickness in the northward direction and a decrease and a complete wedging-out of beds in the southward direction. Thickness is measured in the Tabuk area (340 m), opposed to Jabal Hanadir to the south (40 m). The *Cruziana* Series shows a sharp passage (hiatus?) of shaly siltstone and shaly sandstones with underlying massive sandstones of the Saq Formation. It shows sandstone bedding with minor amounts of sandy shales and shales with a total thickness of 20 m. The sandstones are thinly to massive-bedded quartzose with common cross-bedding and rippling. Thicker sandstone beds show more well-developed current-bedding. Abundant shaly bands preserve trilobite tracks. The *Cruziana* Series can be traced further north in Jordan, where it shows a better development and similar trace fossils identified (Bender, 1963). Alternations of sandstone and shaly bands give evidence of deposition at or near sea level.

Early Paleozoic sandstones are described in the Haql and Jabal Al Lawz quadrangles in northwestern Saudi Arabia.

The Haql quadrangle (Trent & Johnson, 1967b) is located in the extreme northwestern part of the Arabian Peninsula and it captures the Saudi Arabian-Gulf of

Aqaba coastline. Paleozoic marine sandstones crop out along the eastern margin in this quadrangle area (along the Saudi Arabia-Jordan border). The succession includes the Quweira and Ram and Umm Sahm (Undivided) Sandstones. The Quweira Sandstone is described as yellow, buff, brown or reddish-colored, silty or arkosic quartz sandstone. It is massive to cross-bedded and predominantly jointed with a common pebble conglomerate-quartz grit zone at the base that form a nonconformity with older crystalline basement. The Ram and Umm Sahm (Undivided) Sandstones are red and brown with a cross-bedded upper part and massive lower part. The upper part contains abundant warm tubes, rare *Cruziana* trace tracks, possible algal structures, and quartz granule and pebble-rich zones. The lower part is well-bedded buff and tan, massive quartz sandstone which weathers to distinctive rounded forms. Red and grey conglomerates are observed at the base in places.

The Jabal Al Lawz quadrangle is also located in the northwestern corner of the Arabian Peninsula, directly south of the Haql quadrangle (Trent & Johnson, 1967a). Paleozoic sandstones are scarcely found in the northeast corner of this quadrangle area, where both the Quweira and Ram and Umm Sahm (Undivided) Sandstones crop out. The strongly jointed Quweira Sandstone contains massive and cross-bedded sandstones with silty and conglomeratic layers. Grit and quartz-pebble zones that are possibly greywacke are commonly found near the base. The Ram and Umm Sahm (Undivided) Sandstones crop out in magnificent pedestals, spires and buttes of buff, red and brown, massive and cross-bedded sandstones. Similarly, pebble and grit zones are common in addition to strong jointing.

Later field studies of the Siq Sandstone (Hadley, 1973) in the Sahl Al Matran quadrangle describe a peneplanation and deposition of shallow marine basin sediments. The Siq Sandstone consists of red to reddish brown colored; medium- to coarse-grained; thinly-laminated tabular trough cross-bedded; thinly bedded (10 cm) to massive (up to 7 m); pebbly; friable; and arkosic. Conglomeratic beds with clasts of vein quartz are found at the base of the sandstone and several higher levels. The sandstones are generally well-sorted and angular- to sub-angular-grained. The Siq Sandstone is considered immature due to abundance of feldspars and generally unrounded grains (Hadley, 1973). These poorly-rounded, sufficiently-sorted, cross-bedded sandstones suggest rapid deposition in a shallow marine basin. Current action allowed sorting without enough time to thoroughly eliminate detritus.

Another study (Drysdall & Bin Abri, 1978) describes the Siq Sandstone at the base of the sequence in the Al Ula area as red and purple, quartz-feldspathic, conglomeratic (2-3 cm in diameter), cross-bedded sandstone. Rare clasts (10 cm in diameter) of meta-volcanic rocks are recorded along with local conglomeratic lenses (15 m thick) containing basement boulders (25 cm in diameter).

The reconnaissance geology of Wadi As' Sahab quadrangle (Al-Rehaili, 1982), which is mostly covered by sedimentary rocks, only revealed a limited contribution. The unfossiliferous Quweira Sandstone unconformably overlies the Precambrian basement, described as buff, reddish-brown; medium- to coarse-grained; thin-bedded; case-hardened sandstone layers. Undivided Ram and Umm Sahm Sandstones in this area show a lower part that is light-brown, white; medium- to coarse-grained; eolian cross-bedded; thin-bedded sandstone that is broadly equivalent to the Ram Sandstone (Al-Rehaili, 1982). The upper part is brown; medium- to coarse-grained; cross-bedded; thin-bedded; with quartz pebbles in some beds; and rare purple flaggy siltstone.

The Saq Sandstone in the Tabuk and Widyan basins – northwest Arabia (Al-Laboun, 1986) can be divided into lower fluvial and upper littoral to shallow marine facies. The lower part comprises thick extensive braided-river deposits that drained from the near peneplaned source area.

In the later BRGM quadrangle mapping, the Siq Sandstone in Sahl Al Matran quadrangle was described as dark-red to reddish-brown, medium- to coarse-grained, friable, trough-dominant cross-bedded (1-7 m thick) layers of graded beds (2-5 m thick) of sandstone and pebble conglomerate (Hadley, 1987). The lower 10 m of sandstone consist of clear, milky, tan, brown, grey, red and pink, well-rounded, cross-bedded quartz-pebble conglomerates (0.5-6 cm in diameter) in a medium- to coarse-grained arkosic matrix. The reminder of the succession, including the Quweira, Ram and Umm Sahm Sandstones, was not studied in this report. However, trilobite *Cruziana* tracks were observed in the Ram and Umm Sahm Sandstone, suggesting a marine depositional environment (Hadley, 1987), similar to observations in the upper part of the Saq Sandstone in central Arabia.

The Siq Sandstone in Al Bada' quadrangle (Clark, 1986) is composed of dark red to reddish brown, coarse-grained, quartz (slightly feldspathic), and locally cross-bedded, well-bedded sandstone. Scattered quartz pebbles are present, along with thin quartz-pebble conglomerate at the base. The Quweira Sandstone consists of light reddish-brown, medium- to coarse-grained, massive and cross-bedded, arkosic and quartz, well jointed sandstone. A basal conglomerate or quartz grit is present in many places. Interbedded silty sandstone and quartz-pebble conglomerate beds are observed, in addition to minor brown micaceous siltstone. The Quweira Sandstone is probably of continental origin. The Ram and Umm Sahm Sandstones conformably overlie the Quweira Sandstone, consisting of variegated sandstone beds, they weather in a distinctive rounded mesas and buttes, spires and pedestals in places along rectilinear joints, which are well pronounced in the lower part of the sandstone units and they fade away higher up (Clark, 1986). Suggested to cover most of the area of Hadabat Hisma, the Ram Sandstone consists of a variability of light-brown to white colored, massive quartz sandstone with subordinate brown sandy shale or siltstone. Scattered, well-rounded quartz pebbles are present within sandstone beds. Red and grey-bedded sandstone is present near the base. It was suggested that the Ram Sandstone is of continental origin (Quennell, 1951), while others supported the idea that it was deposited in a continental-deltaic conditions (Bender, 1975). Color variations of red and brown rocks in the Umm Sahm Sandstone are similar to the Ram Sandstone. However, it displays more cross beds. Local well-rounded pebbles of quartz and granite are interbedded in places with red, ferruginous sandy shale. The Umm Sahm Sandstone is suggested to have been deposited near-shore in a tidal environment (Bender, 1975).

The Siq Sandstone in the Shaghab quadrangle is described as medium-grained, locally cross-bedded, well-bedded to massive quartz, locally conglomeratic sandstone (Grainger & Hanif, 1989), similar to previous descriptions in the area (Brown et al., 1963; Villemur et al., 1981). Pebbles present, mostly of Precambrian rocks, are concentrated at a basal quartz-pebble conglomerate. This matches in description the lowermost “Basal Sandstone” of the Siq Sandstone defined by Villemur et al. (1981), followed by the “Red Sandstone” and the “Yellow Sandstone.” The Basal Sandstone unit is 100 m-thick, locally cross-bedded, well-bedded, and poorly-cemented sandstone in steep-sloped talus above basement. It is overlain by 60 m-thick red, medium-grained, thinly-bedded, well-cemented and calcareous, vertical cliff-forming deposits of the Red Sandstone. The locally dipping slopes of the third Yellow Sandstone unit are 30 m-thick, described as medium- to coarse-grained, calcareous, vein-quartz-conglomeratic, quartz sandstone (Grainger & Hanif, 1989). Ripple-marked beds in this unit are ferruginous embossments, and less-cemented showing cross-bedding. The Siq Sandstone weathers into a smooth upper surface, in contrast to the overlying Quweira, Ram and Umm Sahm Sandstones, which display rugged terrain. The Quweira Sandstone consists of variegated quartz sandstone, subordinate silty sandstone, quartz-pebble conglomerate and micaceous siltstone. A local basal conglomeratic unit is observed. In the Abu Raqah area, the term “Variegated Sandstone” was assigned to the Quweira Sandstone (Villemur et al., 1981), described as medium-grained, poorly-sorted, steep-cross-bedded, poorly-cemented and calcareous quartz sandstone with some undulating beds of ferruginous sandstone. A distinctive smooth, rounded-weathered morphology of the variegated (yellow-red) Quweira Sandstone was described as “mushrooms” and “pagoda roofs” (Villemur et al., 1981). The undivided Ram and Umm Sahm Sandstones correspond to the “White Sandstone” unit (Villemur et al., 1981). In the lower part of this unit, massive cliff-forming, light-colored, cross-bedded sandstone is observed with subordinate shale and siltstone, whereas the upper part consists of similar sandstones with fewer cross-beds and weathers into “spectacular pinnacles and spires” (Grainger & Hanif, 1989). Disperse distribution of minor quartz-pebble conglomerate is noted in the succession

In the Hadabat Al Ukhayram area southwest of in the Tabuk quadrangle (Janjou et al., 1996), the Quweira Sandstone is coarse-grained, conglomeratic, large-scale trough-, planer- and compound- cross-bedded , multi-meter thick sandstone beds. Conglomeratic intervals contain reworked quartz and rare basement pebbles (up to 15 cm in diameter). Half-meter thick dark-red ferruginous siltstone are regularly scattered throughout the succession. No evidence of bioturbation or reworked fossil fragments is observed in the Quweira Sandstone. A depositional setting of alluvial braided- to straight-river systems is interpreted for this sandstone (Janjou et al., 1996). This deposition takes place during flooding seasons and produces in-channel and transverse bar deposits overlying gravel floor, with rare flood-plain deposits except in the middle of abandoned channels (they erode during channel migration). The basal Risha member of the Saq Sandstone is composed of beige to tan and pink, massive bedded – tens of meters thick – sandstone (Janjou et al., 1996). The upper Sajir member is constituted of white and beige, regular (less-than 5-meter-thick) sandstone beds with brown tarnish (patina). Morphologic and lithologic characteristics of the Risha and Sajir members are comparable to the Ram and Umm Sahm Sandstone descriptions; “massive whitish weathered sandstone,” and “bedded, brownish-weathered sandstone,” respectively (Quennell, 1951; Bender, 1975). Similarly, they match the descriptions of “light-colored whitish to buff-weathering, coarse, eolian cross-bedded continental sandstone,” and “buff to brown, dark-weathering and cross-bedded sandstone” of Powers (1968), respectively.

The Risha member in the Tabuk quadrangle is composed of light-colored, variations of light-beige, to cream, to light-brown and pink, coarse-grained to microconglomeratic, massive-bedded (several tens of meters thick) sandstone (Janjou et al., 1996). Bed bases are conglomeratic lag deposits, mostly quartz pebbles (10 cm in diameter), randomly distributed within bedding. Large-scale trough, low-angle, compound and planar cross-beds are seen with overturning in places. Medium-grained, tabular and planar cross-bedded sandstone beds (decimeter to a meter thick) are well-pronounced near the top of the member, locally overlain by dark-red, purplish thin clayey siltstone. No evidence of reworked bioclastic debris is observed, except for mm-scale bioturbation structures preserved in clayey siltstone intervals (Janjou et al., 1996). A depositional environment is interpreted to represent a fluvial, braided- to straight-river-type, with sediments deposited in channels, or as transverse bars covering lag surfaces. Flood-plains are rare due to rapid channel migration, which also reworks previously deposited bed forms.

The lower contact of the Sajir member with the underlying Risha member in the Tabuk quadrangle is marked by an abrupt change in sedimentological character, along with quartz-pebble lags systematically overlying dark-red clayey siltstone intervals. Beds of 0.1-5.0 m thickness show a sharp morphological and landscape change to ruinous and jagged relief of darker color. Beds are composed of coarse- to medium-grained sandstone, including trough, compound, planar and sigmoidal cross-bedding, overturned in places. These beds are often interspersed with red clayey siltstone, which are regularly interbedded within the sandstone beds, with their thickness increasing upward (up to 8-10 m thick in the upper hundred meters) (Janjou et al., 1996). The fining-upward sequence is occasionally interrupted by overflow (crevice-splay) or flood-plain facies, which contain trace fossils. Whereas these trace fossils are frequently observed throughout the member, vertical tigillites (*Skolithos*) are only observed in the upper hundred meters, where a number of beds are completely colonized. In the uppermost 10 m, tabular or channeled bodies display sigmoidal cross-bedding, sigmoidal bed sets, mud-drapes and cyclic bundles, alternating with sandstone containing tigillites. The depositional environment of the lower part of the Sajir member is likely to be fluvio-deltaic plain with meandering rivers (Janjou et al., 1996). Overflow (floodplain and crevasse-splay) deposits overlie in-channel-dune and transverse-bar deposits. Transition between continental and marine domain is poorly defined in this flat topography. A slight sea-level rise must have resulted in extensive floods to allow this change in depositional character. This allowed for bioturbation to take place and true extensive vertical burrows to develop. These might also suggest a confined domain affected by tides at an outlet realm. Tidal influence is overprinted in tabular deposits (sigmoidal cross-bedding, mud-drapes, neap-spring, etc.) at the top of the Saq Sandstone.

In the Tayma quadrangle (Vaslet et al., 1994), the Risha member of the Saq Sandstone comprises thick brown ledges of massive-bedded (2-5 m thick) sandstone; beige to tan and brown-weathered, coarse-grained to conglomeratic, trough- to planar-cross-beds with basal conglomeratic bases containing white, rounded quartz pebbles and cobbles (up to 8 cm in diameter). Basal-conglomeratic troughs are less frequent to the south of mapping area in the lower part of the member (Vaslet et al., 1994). In the upper part, however, overturned cross-beds are more abundant, associated with planar cross-bedding. Scattered dark-red, ferruginous siltstones (about a meter thick or less) are found throughout the sequence. Burrowing metazoans and shaly remains are absent, except for very rare bioturbation; mm-scale trails, localized in fine-grained sandstone in the upper part of the member. The Risha member was deposited in a braided alluvial fan, with main streams splitting into secondary distributary channels and braided patterns (Vaslet et al., 1994). High-discharge, long-lasting, low-stage ephemeral floods are interpreted from observed sections. Deposition occurred during floods of in-channel dunes and transverse bars over lag gravel floors. High-rate lateral migration is interpreted in channels along with abandonments. Reworking and reactivation of deposited beds is indicative of regressive stage. Abandoned channels and pools are topped by fine-grained particles – silt. These deposits are rarely preserved, frequently eroded during channel migration, except in the middle of abandoned channels.

The Sajir member of the Saq Sandstone is suggested to be recognized as three separate lithosedimentological units in the Tayma quadrangle (Vaslet et al., 1994). From the base to top, the first unit is 250 m-thick, comprising massive-hill morphology. It consists of beige to tan, coarse-grained to microconglomeratic sandstone with trough and planar cross-beds randomly distributed and commonly overturned thick to regular-thickness beds (1-3 m thick). The sandstones are intercalated with numerous dark-red, ferruginous bioturbated siltstone layers, including *Cruziana* and monolobate trails. These siltstone layers are discontinuous in 100 m-wide channel system that is 5-10 m deep and several kilometers long. This unit of the Sajir member represents a distal, alluvial braided plain with channel-fill sequences, similar to the upper part of the Risha member (Vaslet et al., 1994). Flood-plain intervals are characterized in the Sajir member, along with abundance of local marine onlap deposits outside the main distributary channels. The middle unit of the Sajir member is 95 m thick, characterized by abundant small hills and ruiniform relief features. It is composed of beige to cream or whitish, coarse-grained to microconglomeratic sandstone, planar cross-beds and abundant overturned structures. Intercalated 2-4 m thick, dark-red and highly bioturbated siltstone units are observed. Bioturbation includes burrows (cm-scale and conical) and trails (microlobate organisms, *Harlania*, *Cruziana*, and unidentified organisms) (Vaslet et al., 1994). These channel-fill sand bars and marine or flood-plain facies are typical of an upper-tidal deltaic plain environment. The third unit consists of 155 m thick well-bedded sandstones, composed of white to cream, medium- to coarse-grained sandstone, planar and horizontal cross-beds with overturned structures in the lower part of the unit. Sandstone is blackened by a dark ferruginous patina of iron oxides. In the upper part of the unit, meter-thick homogeneous coarse- to medium-grained sandstone channels are observed, together with abundant grey to purple, fine-grained sandstone and siltstone throughout the sequence. The later flood-plain intervals (1-3 meter thick, locally up to 5 m) show rare ball-and-pillow structures. Bioturbation identified in the middle and the upper parts of this unit includes tigillites (*Skolithos*) in the sand facies, and rare trails (*Harlania* and *Cruziana*) in the silty facies.

The described features are representative of a lower tidal environment. The lower unit of the Sajir member infers a fluvio-deltaic, distributary plain traversed by braided streams, dominated by flood discharge which allowed the accumulation of in-channel dunes and transverse bars (Vaslet et al., 1994). Given that these deposits are very flat, it makes it difficult to distinguish the continental-marine boundary. A proposed scenario of a minor sea-level rise might result in an overwhelming inundation of a very large area. These floods are reflected in the presence of fine-grained *Cruziana*-bearing deposits at the top of original fluvio-deltaic in-channel sequences. An increase in marine influence is observed in the middle unit of the Sajir member; supratidal and upper intertidal environment. Facies associations reflect fluvio-deltaic discharge, still, in the form of transverse bars prograding seaward. Common marine on-lap resulted in the deposition of fine-grained, bioturbated sediments, demonstrated in trails and burrows, and marks the end of seaward progradation of deltaic bars in many sequences (Vaslet et al., 1994). The top unit is the most marine-influenced and it corresponds to the deposition of intertidal distributary plain. With continental fluvial influx being the character of this unit, fluvial channels were widely redistributed into tidal channels, sandy foreshore bars and sand flats in an intertidal zone. Tigillites were introduced in protected sand succession during calm times.

2.2.2.3 Southern Arabia

The Wajid Sandstone in southern Arabia (Powers et al., 1966; Powers, 1968) is described as thick, poorly-sorted, cross-bedded sandstone, with the upper part incorporating rare thin silty or dolomitic (lacustrine?) beds. These observations repeated in other sections in the area between Jabal Wajid (19° 15’ N) and Bani Ruhayah (19° 50’ N).

Hydrologists from Itlaconsult redefined the Wajid Formation in southern Arabia. Drill-hole descriptions displayed white and rarely reddish, fine- to coarse- grained friable quartzose sandstone, containing fine beds of white or variegated shale, dolomitic layers and intervals of quartzitic and ferruginous cementation (Lloyd, 1968). The Wajid

Formation was interpreted to represent continental to deltaic depositional environment, which also contains uncertain fossils.

Later sedimentologic studies regarded the Wajid Sandstone as epicontinental sea detrital sequences composed of cross-bedded, slightly-cemented sandstone (including calcareous cement), and containing intercalations of micaceous sandstone, siltite with manganese-oxide concretions, and red silty clay associated with hardground (Alabouvette & Villemur, 1973). Ferruginous sandstone layers were recorded in the middle of the sequence and marine character was typified in the lower part of the formation by identified *Cruziana* and *Skolithos* trace fossils. Erosional surfaces were identified by a gradient of 50° within the sequence, filled with coarser-grained sandstone and conglomeratic beds, cross-bedded and slumped structures.

The USGS mapping of this area (Greenwood, 1981a; 1981b; Pallister, 1982) has led to divide the Wajid Sandstone into two units separated by an angular disconformity, locally at 60°. The Shum member is the lower unit and is characterized by a sandy facies marked by quartzose composition with traces of feldspars. Evidence of gravitational slumping is present, which do not exceed the limits of the unconformity. The Ilman member is marked at the base by a thin layer of quartz conglomerate boulders in a planer-bedded quartzo-feldspathic matrix (5-15% feldspathic) with interbedded red ferruginous siltite. No evidences of deformation are present in this member. The local Hijinah uplift, a Shum-member synchronous felsic granite pluton emplacement might be the cause of deformation in this unit of the Wajid Sandstone (Stoeser & Greenwood, 1984). Another theory that supports the deformation of this unit is seismic activity resulting in slumping in water-saturated sediment setting (Pallister, 1982).

Studies by Dabbagh and Rogers (1983) on the Wajid Sandstone in Yemen were described as braided-stream, cross-bedded inclined graded sequences within imbricated channels-fluviatile deposits (Geuken, 1966). Northwards, south of the Arabian Shield, homogeneous sequences of finer-grained shallow marine deposits show rare cross-beds, no evidence of channeling and trace fossils are common in tidal and subtidal environments (also bilobate traces and tigillites).

Later studies ("Geology of exploration work in the Qasim and Wajid Areas," 1984) led to the subdivision of the Wajid Sandstone into three units. The Ayn Formation is characterized by basal conglomerates and arkosic cross-bedded sandstone (in ferruginized channel bases), with a display of large slumps. This unit is believed to be correlatable to Shum member of Pallister subdivision of the Wajid Sandstone (Pallister, 1982). A second intermediate unit (Wajid Formation sensu) comprises basal ferruginized surfaces and planer cross-bedded inclined sandstone prograding northwards. The upper third unit of Bani Khurb Formation consists of coarse-grained cross-bedded sandstone with kaolinic cement and granite blocks present.

Studies by Minoux and Janjou (1986) on the Wajid Sandstone outcrops in northern Jabal Wajid enabled the subdivision of this unit into four sedimentary bodies. The Dibsiyah member unconformably overlays the Precambrian basement with basal conglomerates containing rounded quartz boulders (1-8 cm in diameter) in a quartzose matrix with calcite and hematite cement. This layer is overlain by centimeter-to-several tens of meter thick cross-bedded and inclined conglomeratic sandstone, psammitic intercalations and bioturbated beds (including *Skolithos* and other unilobate trails). This member is overall graded, with massive beds increasing in the upper part and tigillites appearing only 50 m from the base. The Sanamah member is found as erosional surfaces channeling the Dibsiyah member. With a base marked by heterogeneous rounded boulder conglomerates (up to 7 cm in diameter), the sequence is coarse-grained, locally quartz-conglomeratic, barren sandstone with variable medium- to fine-grained psammitic sandstone above ferruginous hardground. Bedding is nonexistent or indistinct in a feldspar-rich basal layer. The Sanamah member shows lateral discontinuity, wedging out by members below and above. Fluviatile sediments at the base of this member evolve into deltaic deposits in channel-fills scoring the Dibsiyah member, which show rare meter-scale slump structures. The Khussayyayn member unconformably overlies the Dibsiyah and Sanamah members of the Wajid Sandstone. It is characterized by medium- to coarse-grained homogeneous-quartzose sandstone with common prograding beds that are 10° to 30° inclined. The sandstone unit is intercalated with cross-bedded, graded and imbricated-festoons top. The Khussayyayn member is interpreted as an extensive and persistent fluviatile system. The Juwayl member is also marked by major erosional surfaces in places, notching the overlying Sanamah member north to Jibal Juwayl. Locally inclined at 40°, this surface mark coarse-grained conglomeratic (quartz boulders) beds, followed by fine- to medium-grained massive sandstone. Reworked decimeter- to meter-scale fine-grained sandstone fragments are displayed in this sequence, along with evidence of microchanneling and slumps, and absence of bioturbation. Mud currents (solifluction) observed in the lower part of this member might indicate cold or periglacial climate, whereas the middle and upper parts display fluviatile to fluviatile-marine characteristics of sedimentation. It is later suggested in Kellogg et al. (1986) to correlate the Juwayl member of the Wajid Sandstone possibly with the Ordovician Sarah

Formation in the Qasim region in central Arabia. Evidence of Late Ordovician glaciation are present in the Wajid Sandstone in other studies (Smith, D. C. & Allen, 1984), indicating possible fluviatile-glacial coarse-grained interbedding containing erratic blocks.

2.3 Age Definitions and Interpretations

The different studies that covered this succession in different localities have produced different age interpretations. These variable interpretations are based on multiple justifications, mostly related to ichnofacies dating and regional correlations. Here, we illustrate some of these age definitions of the Cambro-Ordovician succession.

2.3.1 Jordan

Old sedimentary deposits were metamorphosed in the Precambrian and later produced a plane erosional surface underlying later Cambrian deposits. These are suggested to be equivalent in age to the Early Paleozoic succession in northwest Saudi Arabia (Quennell, 1951).

Quennell’s studies in Jordan implied a Cambrian age for the studied sandstones. Based on fossil content, the deposition of these sandstones coincides with the Lipalian Interval, marking the beginning of the Cambrian (Quennell, 1951). The Lower Quweira Sandstone contains no fossils, and it is overlain by the trilobite-bearing beds of the Burj Limestone Group with an interpreted age of Early to Middle Cambrian from previous work (Blanckenhorn, 1912; 1914; King, 1923; Blake & Ionides, 1939; Picard, 1942). This places the underlying Lower Quweira Sandstone to be of an Early Cambrian age (Quennell, 1951). Dolomite-limestone-shale marine sequences found in other localities northwards similarly dated as Early to Middle Cambrian age (Blanckenhorn, 1912; Dienemann, 1915; King, 1923; Richter & Richter, 1941; Picard, 1942; Quennell, 1951; Burdon & Quennell, 1959).

Later Studies done by Bender (1975) placed the Quweira Series below fossiliferous Early Ordovician deposits that contain uppermost Early Cambrian or lowermost Middle Cambrian fossils near the Dead Sea area (Bramkamp et al., 1963). The succession was thus assigned the age of Cambrian to Early Ordovician (Bender, 1975). Trace fossils found in the Ram Sandstone indicate an Arenigian (Early Ordovician) age (Bender & Huckriede, 1963).

2.3.2 The Great Arabian Basin

Early Paleozoic sedimentary deposition is suggested to have followed the last deformation phase of the Pan-African Orogeny (580-550 Ma). There are two hypotheses that infer the age of first deposited Paleozoic barren sandstones (Vaslet, 1987, p. 90). The first hypothesis indicates a Precambrian-Cambrian boundary, and it is adhered by previous work in the area (Powers et al., 1966; Powers, 1968). This age derivation is based on correlations with sequences of assumed equivalence in Jordan (the lower part of the Saq Sandstone in central Arabia with the Quweira Sandstone and Burj Limestone Group in Jordan).

The second hypothesis infers an Infracambrian age of the basement-cover boundary. This hypothesis is deduced from results of radiometric chronology on the most-recent magmatic events in the Early Cambrian basement and associated Precambrian basement (Delfour, 1970). This study described the second episode of the Najd deformation to be responsible for the formation of grabens in the northwest-southeast orientation in which detrital, carbonate and volcanic facies of the Jibalah Group were deposited. The deformation occurred after the late plutonic granite intrusion; 570 ± 19 Ma, utilizing Rb/Sr methods (Ekren et al., 1987). This was confirmed by further studies (Calvez et al., 1983) which dated the Jabal Rahaba granite (boulders of which are reworked within Jibalah Group) as 574 ± 28 Ma (Rb/Sr). Both of these studies indicate an Early Cambrian age for the Jibalah Group. The first deposits of the Yatib Formation, which fill paleohollows in the planed basement, would be of Middle to Late Cambrian age in terms of the second hypothesis. The lower part of the Saq Sandstone is assigned a Tremadocian or Arenigian (Late Cambrian or Early Ordovician) age.

2.3.2.1 Central Arabia

The Saq Sandstone is roughly considered of a pre-Early Ordovician age and is correlative with the Cambrian Quweira Series in Jordan (Steineke et al., 1958). Previous work has suggested a marine character of the Cambrian sediments of the Saq Formation in this area (Vroman, 1944; Bender, 1963; McKee, 1963). It was later revised to Cambrian-Ordovician (Powers et al., 1966; Powers, 1968). The lower part of this sequence (equivalent to the Siq and Quweira Sandstones in the northwest) is correlated with equivalent limestone-shale-trilobite units in the Dead Sea area and it can be assigned with confidence to Middle Cambrian time. Trilobite tracks samples collected in Jabal Saq and in other localities in the northwest are confined to the upper part of the Saq and Ram-Umm Sahm Sandstones, occurring in red-purple thin lenses of shale. These samples were identified by Preston E. Cloud, Jr., to be of probably of Early Ordovician age (Powers, 1968).

The Burj Limestone Group of the Quweira Series in Jordan infers an uppermost Early Cambrian or lowermost Middle Cambrian age (Daniel, 1963) and the Ram Sandstone fossils infer an Early Ordovician age. This indicates that the Quweira and Ram Sandstones are equivalent to parts of the Saq Sandstone in central Arabia.

It is suggested that traces of biologic activity recorded in the upper part of the Saq Sandstone in central Arabia are alleged to have no chronostratigraphic value (Vaslet, 1987). A study of a hydrogeologic borehole by the Saudi Arabian Ministry of Agriculture and Water Resources in the Cambro-Ordovician sequence of central Arabia has made it possible to sample material from the upper part of the Saq Sandstone. This borehole intersects 116 m of the Sajir member. Paleontological studies identifies associations of chitinozoans and acritarchs imply a Late Arenigian to Llanvirnian (Early to Middle Ordovician) age in this interval, which coincides with the Early Llanvirnian age of the overlying Qasim Formation (Vaslet, 1987).

2.3.2.2 Northwestern Arabia

The Quweira Sandstone in northwest Arabia was assigned a Cambrian age from correlations with Jordan; see Bender (1963); (Bramkamp et al., 1963).

Siltstones recorded in the upper part of the Ram and Umm Sahm Sandstones (Undivided) are fossiliferous in places and show variety of Arenigian (Early Ordovician) arthropod tracks (Al-Rehaili, 1982).

A spore zone in the lower part of the Saq Formation in the Tabuk area is possibly correlative with Early Cambrian *Skolithos* trace fossils (Helal, 1968). The base of the overlying *Cruziana* Series, marked by a hiatus with the underlying units, shows Tremadocian-Arenigian (Early Ordovician) fauna. Some *Cruziana* tracks and graptolites, observed in this unit in the northwest and in central Saudi Arabia, possibly suggest a Tremadocian-Caradocian (Early to Late Ordovician) age. These deposits are widely exposed in the Tabuk area and they are suggestive of an Ordovician sea transgression

The littoral to shallow-marine- deltaic deposits in the upper part of the Saq Sandstone consist of argillaceous sandstones, micaceous siltstones and shales, corresponding to the Early Ordovician first regional marine invasion in Arabia (Al-Laboun, 1986), marked by Tremadocian-Arenigian (Early Ordovician) age arthropod *Cruziana* tracks. The lower units of the Siq and Quweira Sandstones in the Tabuk basin are assigned to the Cambrian age based on the presence of Middle Cambrian trilobites in the regionally-equivalent interbedded limestone and shale units near the Dead Sea, implying a Middle Cambrian to Early Ordovician age for the Saq Sandstone (Powers et al., 1966); (Al-Laboun, 1986).

2.3.2.3 Southern Arabia

Powers (1968) regarded the azoic Wajid Sandstone as Early Permian or older (?) continental deposits, because it is overlain by the Khuff Formation (Permo-Triassic). It was then assigned a Cambrian (?) to Ordovician age based on stratigraphic position, with relation to the overlying Faw Formation (Lloyd, 1968). Trace fossils later helped to assign a Cambrian-Ordovician age instead of the Permian.

Microflora samples indicated a Middle (?) and Late Cambrian to Caradocian (Late Ordovician) age for the Wajid Sandstone. These conclusions were reached by subsurface drill-hole data analysis (Lloyd, 1968; Brown, 1970; Hadley & Schmidt, 1974; McClure, 1980), which date layers overlying the Wajid Sandstone to be of Silurian age. Minatome Corp ("Geology of exploration work in the Qasim and Wajid Areas," 1984) identified algal spores, chitinozoans and acritarchs, characteristic of Late Ordovician age in a clayey-silty layer of the Wajid Sandstone. The Wajid Sandstone then represents a succession of Cambrian (?) to Ordovician age, comprising several sedimentary units separated by erosional surfaces.

2.3.3 Other Areas

Regional correlations can be established based on possible similarities with Paleozoic successions in northwest Africa, where a Tremadocian or Arenigian (Middle Cambrian and Early Ordovician) unconformity marks a transgression over all of Morocco (Destombes et al., 1985). Paleozoic sequences in the Hoggar region in Algeria have dated equivalent rocks as Tremadocian (Early Ordovician) (Legrand, 1964; 1973; 1985).

2.4 Paleocurrent Analysis from Previous Work

Transgressive events taking place in the Early Paleozoic studied succession in Jordan indicate a marine invasion from north or northwest (Quennell, 1951). McKee proved a transport direction observed from cross-beds dip to suggest that the Cambrian sea had invaded the Middle East from the northwest, not the southeast as previously interpreted (McKee, 1963).

Paleocurrent directions in the Risha member of the Saq Sandstone in central Arabia indicate a flow direction ranging between N 30° and N 70°, and locally N 120° at latitude 25°, and between N 170° and N 20° in the Ha'il region, with an overall flow direction mean towards the northeast (Vaslet, 1987). Paleocurrent flow direction in the Sajir member in central Arabia is observed to be at a wider range compared to the Risha member, with directions ranging between N 15° and N 60° in the Ha'il region and between N 0° and N 60° in the Baqa'-Jabal Saq region (Vaslet, 1987).

Trough cross-beds within the Siq Sandstone, studied in northwest Arabia, including measurements collected in the Sahl Al Matran quadrangle area, indicate a transport direction of northwest and northeast (Hadley, 1973; 1987).

Paleocurrent direction analysis of the Wajid Sandstone in southern Arabia suggest a north-northwestward and eastward flow direction–towards the Arabian Shield (Alabouvette & Villemur, 1973). Variable northward paleocurrent directions in two locations in southern Arabia in a different study support a continent-open sea polarity scenario, indicating that the Wajid Sandstone sediments are originated from the Hadramaut or Dhofar areas, south and southeast of Saudi Arabia respectively, not from the Precambrian basement of the Arabian Shield (Dabbagh & Rogers, 1983). Flow directions in the Khussayyayn member of the Wajid Sandstone was estimated as north-northwest and northeast (Minoux & Janjou, 1986).

2.5 Petrographic Analysis from Previous Work

Many parts of the Cambro-Ordovician succession where described as feldspathic to quartzose from field observations. Limited published petrographic description of the Siq Sandstone in the northwest (Hadley, 1973) show; 45% quartz, mostly monocrystalline; 25% cloudy but generally fresh microcline; 10% plagioclase; 5% rock fragments; and 3% opaques. Pore space was calculated to be 30% with 5% filled with microcrystalline quartz cement. No other studies were found to support petrographic analysis of the full succession.

Later work by Hadley (1987) of samples collected from the Siq Sandstone at Jabal Rubtayn near Al Ula shows a sandstone matrix of 40-60% monocrystalline and polycrystalline quartz, 20-30% potassium feldspar, 5-15% plagioclase, 3-8% rock fragments, and 1-3% opaque minerals, with original calcite cement replaced by microcrystalline quartz and pore count as high as 25%.

CHAPTER 3

METHODOLOGY

The purpose of this study is to attempt to describe the sedimentology and the lithostratigraphy of the Early Paleozoic, pre-Ordovician glaciation- and Silurian marine invasion-, Cambro-Ordovician clastic succession in northwest Saudi Arabia. This was planned by first measuring and describing a number of outcrop sections. Two study areas near both Al Ula and Tabuk were selected based on outcrop stratigraphic position and accessibility (Figure 3.1). Two locations were considered to demonstrate possible variations in depositional facies, facies associations, facies distribution and paleogeography, if any are present. Although this succession is found elsewhere in the northwest[1], it was decided to limit the focus of this thesis study to selected study areas only for time and logistics concerns related to this field study. Representative samples were collected for later petrographic analysis. Samples were collected at random from the various locations in the succession for the purpose of deriving an initial insight about the lengthily-debated petrographic characters of these sandstones. These were only supported by limited published work. The petrography work in this study is not meant for a full petrographic characterization of the succession.

[1]Sandstone outcrops recorded down the east-west Highway-394 towards the Gulf of Aqaba near the Saudi Arabia-Jordan border in the northwest. This is similar to the third study area by Helal (1968). Recorded coordinates for this area it is: N 28° 52.759’, E 35° 37.803’.

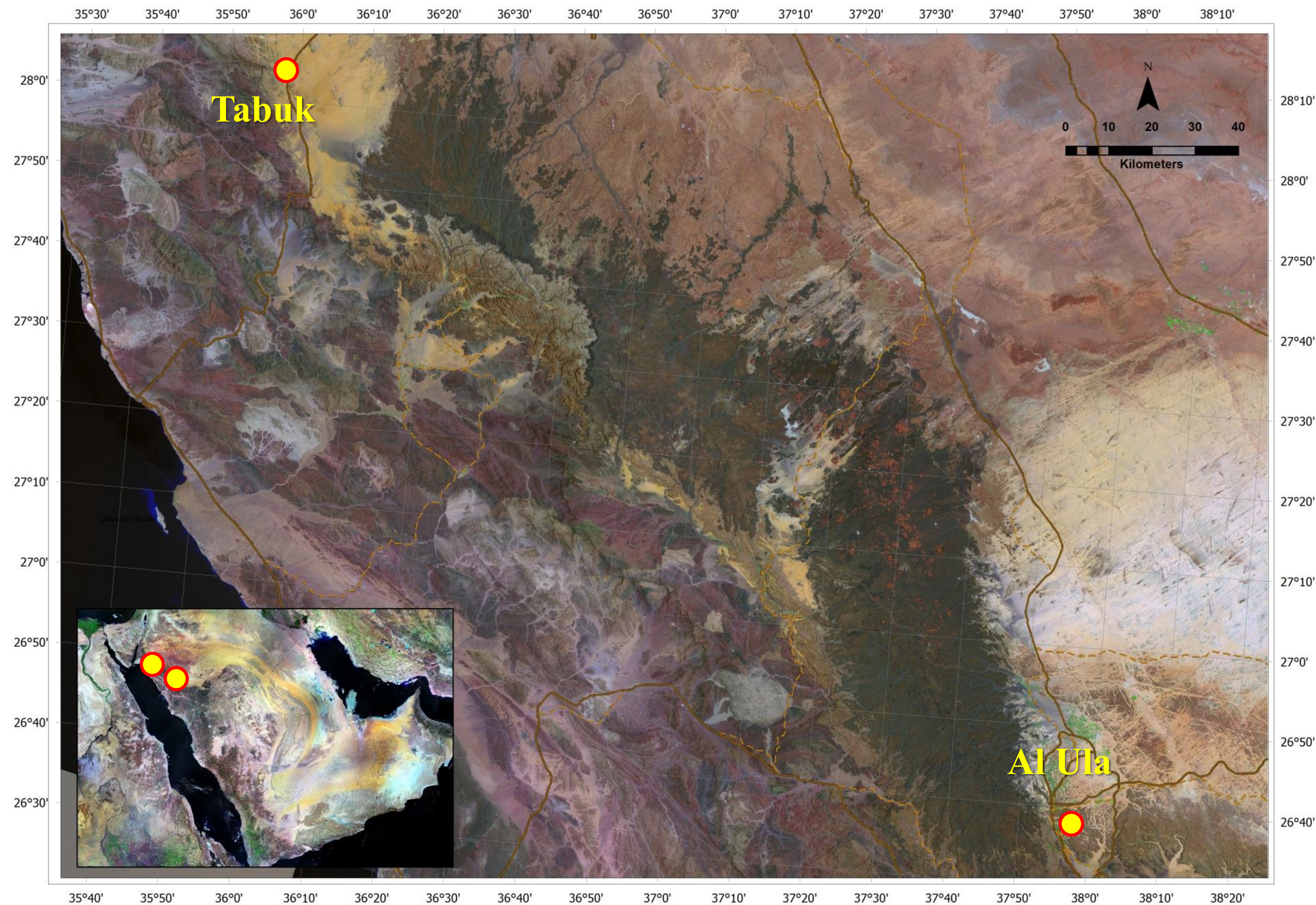


Figure 3.1: Map of northwest Saudi Arabia highlighting the locations of the two study areas in this study near both Al Ula and Tabuk (estimated distance between the two study areas is ~270 km).

3.1 Measured Sections

Potential outcrops were identified and selected during previous reconnaissance trips to both study areas near Al Ula and Tabuk. For the purpose of proper organization, studied outcrops in the Al Ula and Tabuk areas were assigned the letters U and T, respectively. Study lines-of-section were planned in each study area, where measured sections on each line have the same first digits, i.e. U1XX. A total of 5 lines-of-section were studied in the Al Ula area and Mada'in Saleh, and one line-of-section was studied in the Tabuk area (Figure 3.2, Figure 3.3 and Figure 3.4). Each measured sections was assigned a two-digit number following the letter for study area and digit for line of section, i.e. U101. Composite sections can be constructed in each line-of-section, since sections were measured down the apparent dip direction; hence older to younger rocks. Dip direction is estimated at NEE in the Al Ula area and ENE in the Tabuk area. Table 3.1and Table 3.2 summarize the details about measured sections in both study areas.

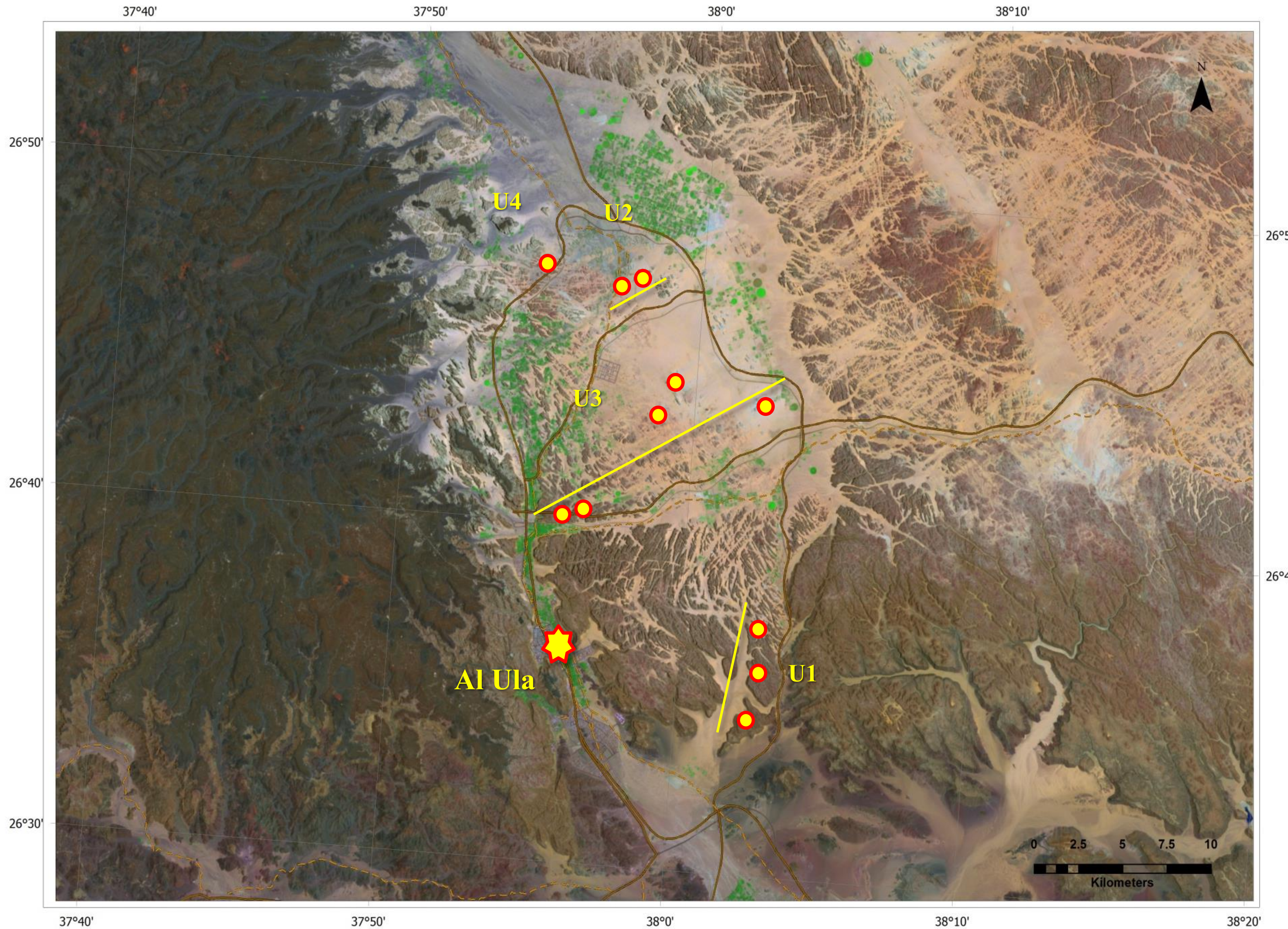


Figure 3.2: Map displaying locations of measured sections in the Al Ula area (except for area U5).

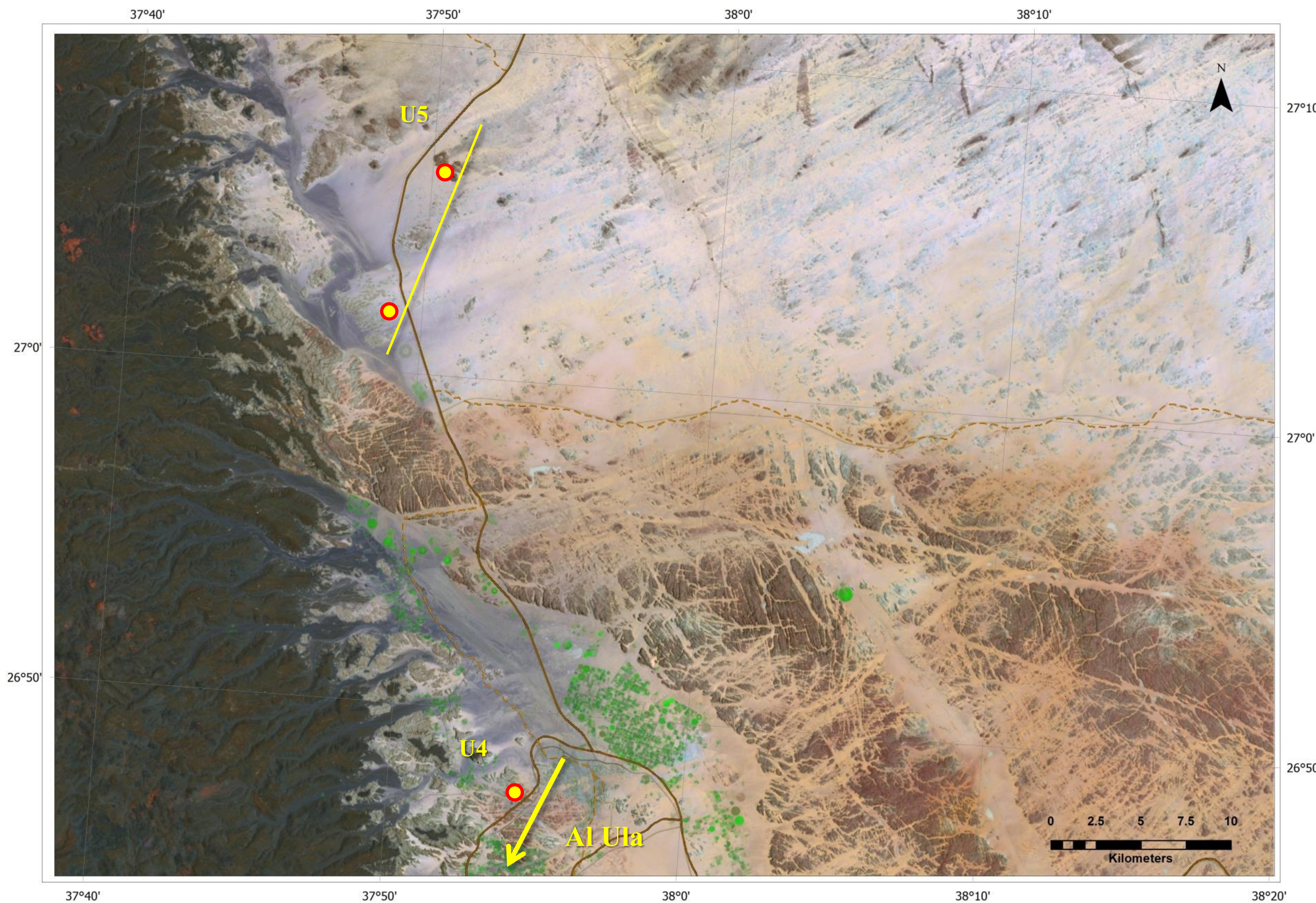


Figure 3.3: Map displaying the northern part of the Al Ula area, showing the location of area U5 and U4 for reference. The arrow shows the direction towards Al Ula.

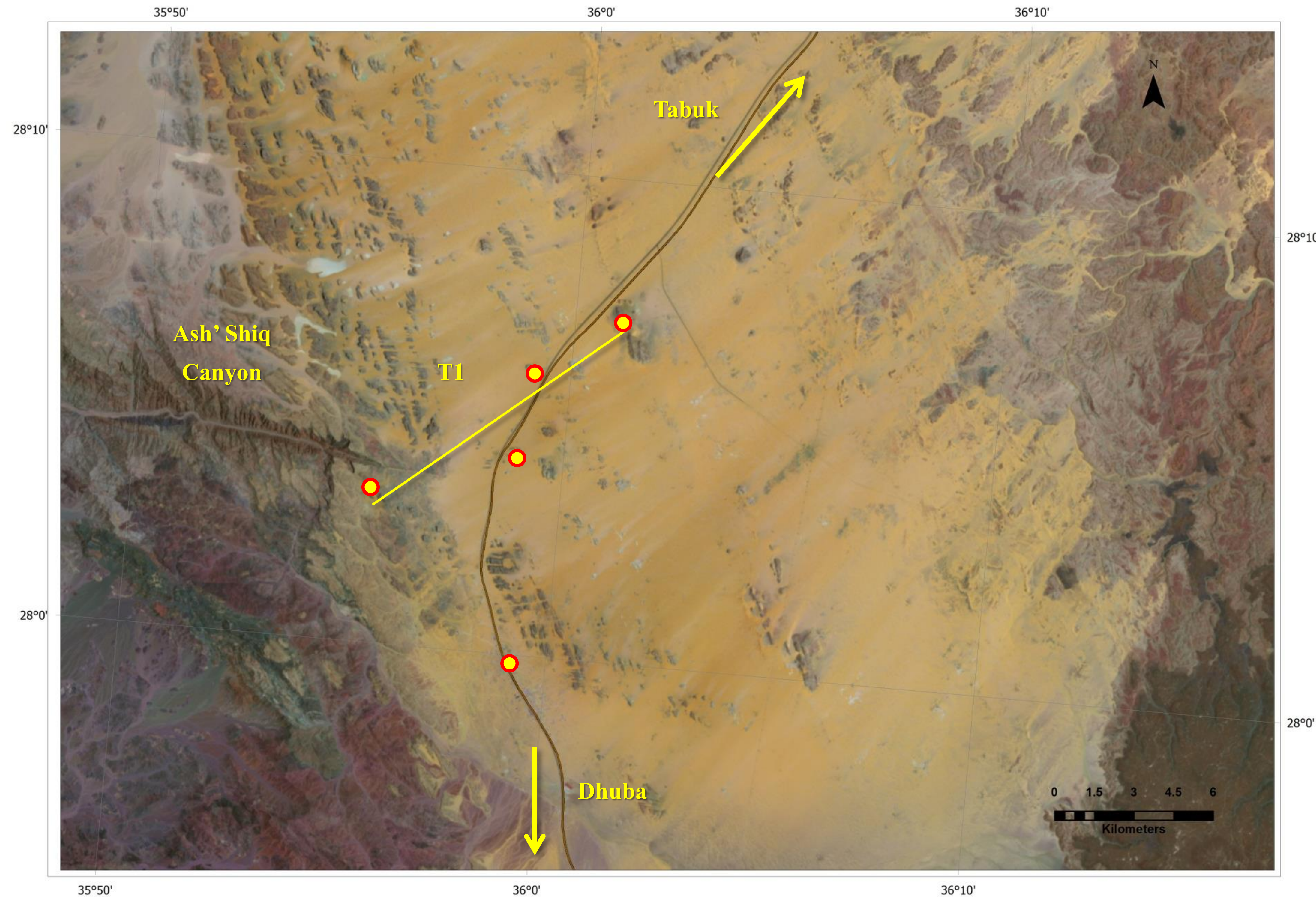


Figure 3.4: Map displaying locations of measured sections in the Tabuk area with reference to the location of (Shai'b) Ash' Shiq (Canyon), southwest of the city of Tabuk. Arrows show directions towards both Tabuk and Dhuba.

Table 3.1: Measured sections in the Al Ula area

Line of Section	Measured Section	Location Remarks	Coordinates (dd° mm.mmm’)
U1	U101	Wadi east of the town of Al Ula. Composite section lie unconformably on top of basement and measured sections are in succession	N 26° 34.718’, E 38° 02.065’
	U102		N 26° 36.405’, E 38° 02.533’
	U103		N 26° 37.468’, E 38° 02.337’
U2	U201	Al Khuraimat (Mada’in Saleh)	N 26° 46.934’, E 37° 56.759’
	U202a	Ad’ Diwan (Mada’in Saleh)	N 26° 47.571’, E 37° 57.739’
	U202b		N 26° 47.380’, E 37° 57.950’
U3	U301	Aligned with the beginning of Highway-70 north of Al Ula and heading east towards Ha’il	N 26° 39.961’, E 37° 55.345’
	U302		N 26° 40.195’, E 37° 56.238’
	U303		N 26° 43.313’, E 37° 58.679’
	U304		N 26° 44.186’, E 37° 59.022’
	U305		N 26° 44.000’, E 38° 02.300’
U4	U401	Continuous section, commonly covered by Tertiary lava flow deposits	N 26° 47.579’, E 37° 54.589’
U5	U501a	Area further north of Al Ula (~ 55 km) where morphology of outcrops changes	N 27° 02.126’, E 37° 48.999’
	U501b		N 27° 01.858°, E 37° 48.828’
	U502		N 27° 07.440’, E 37° 50.693’

Table 3.2: Measured sections in the Tabuk area

Line of Section	Measured Section	Location Remarks	Coordinates (dd° mm.mmm’)
T1	T101	As’ Siq (pronounced: Ash’ Shiq) reference section (Bramkamp et al, 1963)	N 28° 03.287’, E 35° 55.629’
	T102	Outcrop behind Ash’ Shegri Gas Station, Ash’ Shegri Village, Tabuk region	N 27° 59.901’, E 35° 59.200’
	T103a, b	Off Highway-80 heading east from Bajdah Village towards the city of Tabuk	N 28° 04.017’, E 35° 58.964’
	T104		N 28° 06.004’, E 35° 59.072’
	T105		N 28° 07.200’, E 36° 00.816’

3.1.1 Outcrop Rock Description

Ordinary outcrop description sheets were used to measure and describe outcrops. Criteria utilized in the descriptions included outcrop observation angle, measured thickness (in meters), grain size and sedimentary structures, lithology, color-coded facies, paleocurrent directions, sample number and general descriptions and remarks. Each criterion was logged in a separate column (Figure 3.5). Patterns and changes in grain sizes, sedimentary structures and lithology were recorded with appropriate descriptions. When accessible and preserved, paleocurrent direction measurements were logged in cross-bedded sets.

A number of tools were used throughout this exercise to help record observations accurately. These include a hand lens, chisel and pick rock hammers, protective eye glasses, measuring tape, Jacob staff, Brunton compass, sketching board, pack back, pocket knife, camera, pencils and other sketching gear and an appropriate number of blank sketching log-paper. Logistical equipment utilized to enhance field work was also prepared. These include sampling bags, satellite phone, backup batteries, vehicle survival and off-road kits, first aid kits, GPS device and maps. Proper clothing and hiking gear was also used to ensure a safe working experience.

A total number of 20 sections were measured in both study areas with a total footage of about ~ 622 m (2040 ft.). These measured sections were digitized and are found in Appendix A.

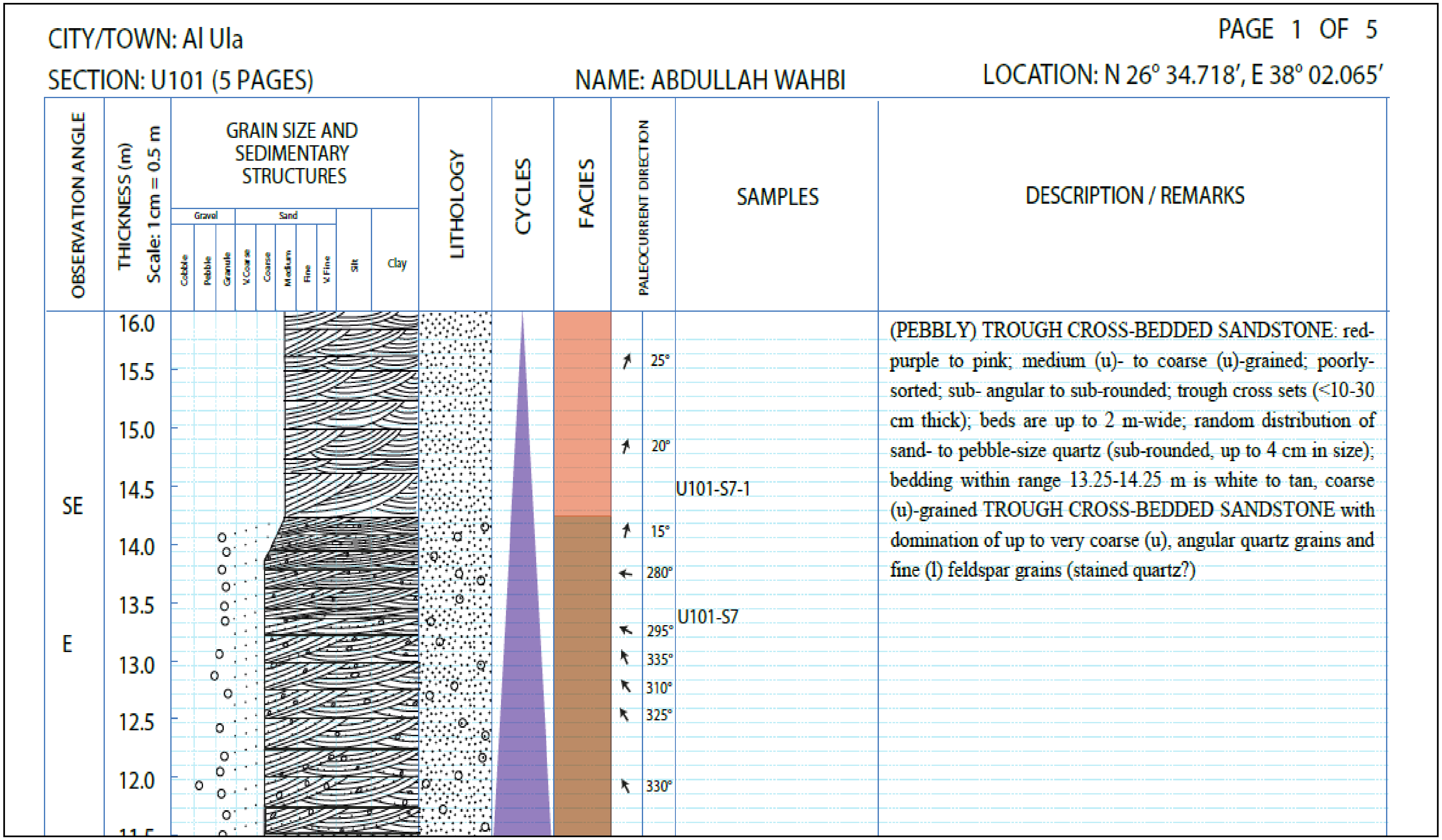


Figure 3.5: Example of a measured outcrop sections as found in Appendix A.

3.2 Paleocurrent Data Collection

Paleocurrent direction data was collected throughout the succession in both the Al Ula and Tabuk areas. The dataset comprises measurements of dip-direction azimuth angles collected from cross-bedded sets. Where measurements were not collected in every logged bed or set due to accessibility, collected measurements included sets from different facies that display cross-bedding and different sandstone units. Multiple measurements were often logged for one surface where accessibility is considered excellent. Paleocurrent data measurements and their locations within the succession are logged in the measured sections (in Appendix A) with both numbers and arrows that display their different directions. This dataset help demonstrate paleocurrent data analysis.

3.3 Thin section petrography

Sandstone samples were collected from the various sandstone units in both study areas. The samples were collected from all studied facies (Appendix A). Samples could not be collected within the Mada'in Saleh area (area U2) due to restrictions at this historical site.

3.3.1 Thin Section Preparation

The samples were cut and standard thin sections were prepared. Prior to thin section manufacture, the rock samples were vacuum-impregnated with blue-died epoxy resin. This blue pore-filling resin helps to determine the amount and character of the different types of porosity in these samples. After the impregnation, the samples were mounted on glass slides and were ground and polished until they reached the optimum thickness of 30 µm (microns).

3.3.2 Thin Section Staining for K-Feldspars

Previous work have suggested that part of the succession, i.e. the Siq Sandstone show greater concentrations of feldspar components when compared with other parts of the succession, i.e. the Quweira and Saq Sandstones. A number of the thin sections were stained with sodium-cobaltinitrite, which stains potassium-feldspars with a bright-yellow color. Staining for K-feldspars helps to demonstrate the quantitative interpretation of the feldspar component in this petrographic study. The procedure of staining was done following the steps cited by Van Der Plas (1966, pp. 47-52).

The limited number of samples stained were later disregarded. The yellow staining for K-feldspars in these thins sections prevented the description and counting of diagenetic components associated with the chemical dissolution of feldspars. Components such as kaolinites and clays were obscured by the Na-cobaltinitrite stains. The decision was made not to stain the remaining thin sections for K-feldspars using Na-cobaltinitrite and to have the stained thin sections remade for descriptions and comparisons. K-feldspar components were, instead, identified and described based on their optical and petrographic properties, which include birefringence, cleavage and microscopic twinning, where present.

3.3.3 Thin Section Descriptions

Full petrographic descriptions of each thin section were made, in addition to point counting. These descriptions characterize the petrographic properties of all different rock-components. These properties include grain size, grain shape, sorting, defined grain composition, diagenetic features including cementation, dissolution, grain replacements and alterations, as well as the nature of the pore system. Some specific descriptions limited to certain rock components were stated when needed.

3.3.4 Thin Section Point Counting

Semi-quantitative data was obtained by point counting each thin section using a point counter. A total number of 300 points was counted in each thin section, since this number is commonly accepted as providing a statistically-accepted dataset. A total number of 12 components were counted in each thin section in this study. These cover both detrital and authigenic components, in addition to different varieties of porosity (see table in Appendix A).

Total counts were recorded in a spreadsheet, where the data can be manipulated to determine percentages of each component, in addition to porosity calculations. A number of ternary relationships were demonstrated as part of the results, using normalized values for detrital components. Ternary diagrams were plotted using the sandstone classification of Folk et al. (1970). Different figures were produced to evaluate any trends in studied components in the thin sections.

CHAPTER 4

RESULTS

After field work was completed with all measured sections logged and all samples collected, the acquired data was analyzed. Facies were described and interpreted, and then grouped into facies associations to determine depositional settings. Measured footage of each facies was plotted in a number of pie charts to demonstrate facies distribution both lithostratigraphically and paleogeographically. Paleocurrent direction measurements were plotted based on their facies and lithostratigraphic distribution. Thin sections were described and point-counted, and the data were analyzed to determine any changes or trends.

4.1 Facies Descriptions, Facies Associations and Facies Distribution

Facies were identified throughout all the measured sections and are listed here with full descriptions of their sedimentological characteristics. Sequences of these facies are then determined in terms of facies associations, which enables identification of variations in depositional settings throughout the studied succession. The list of facies covers all studied sandstone units, since some facies occur in more than one unit. Facies distribution highlight variations in the relationships among the different facies throughout the studied succession in both the Al Ula and Tabuk areas, which allows an understanding of the changes in depositional settings and processes.

4.1.1 Facies Descriptions

A Total of 14 sedimentary facies were identified throughout the measured sections in both the Al Ula and Tabuk areas. Facies were recognized based on identifiable sedimentary textures and structures and were listed in an order based on sets' descriptions and thicknesses. Different cross-bedded sandstone facies were distinguished using the definitive classification schemes of McKee and Weir (1953) and Allen (1963). Textural features such as pebble-size and pebble-concentration allowed subdivision of facies into further sub-categories where this was considered appropriate. This facilitates differentiation of facies in terms of depositional energy and variation in depositional setting. Facies are therefore listed in a descending order with respect to change in set thickness, grain-size, energy of deposition, and amount of deformation during or immediately post deposition. Facies occurrences per sandstone unit for both the Al Ula and Tabuk areas are presented in Table 4.1 and Table 4.2. More specific allocation of each facies is found in Appendix A.

Table 4.1: Facies occurrences per sandstone unit in the Al Ula area

Facies Number	Facies Name	Stratigraphic Unit				
		Lower Siq Sandstone	Middle Siq Sandstone	Upper Siq Sandstone	Quweira Sandstone	Saq Sandstone
1	Sandy Cross-Bedded Conglomerate				X	
2	Conglomeratic Trough Cross-Bedded Sandstone				X	
3	Pebbly Trough Cross-Bedded Sandstone		X	X	X	X
4	Trough Cross-Bedded Sandstone		X	X	X	X
5	Planar Tabular Cross-Bedded Sandstone		X		X	X
6	(Pebbly) Tangential to Sigmoidal Cross-Bedded Sandstone	X	X		X	X
7	Thinly-Bedded Tangential to Sigmoidal Cross-Bedded Sandstone	X	X	X	X	X
8	Low-Angle Tangential to Sigmoidal Cross-Bedded Sandstone		X		X	
9	Lenticular- to Wavy- and Ripple-Laminated Sandstone		X	X	X	X
10	Flat-Laminated to Massive Sandstone		X	X	X	X
11	Deformed Sandstone			X	X	X
12	Cross-Bedded Sandstone with Overturned Foresets	X	X	X	X	X
13	Intensely-Deformed Sandstone	X			X	X
14	Very Poorly-Sorted Paraconglomerate					

Table 4.2: Facies occurrences per sandstone unit in the Tabuk area.

Facies Number	Facies Name	Stratigraphic Unit		
		Upper Siq Sandstone	Quweira Sandstone	Saq Sandstone
1	Sandy Cross-Bedded Conglomerate			
2	Conglomeratic Trough Cross-Bedded Sandstone			
3	Pebbly Trough Cross-Bedded Sandstone	X	X	
4	Trough Cross-Bedded Sandstone	X	X	
5	Planar Tabular Cross-Bedded Sandstone		X	X
6	(Pebbly) Tangential to Sigmoidal Cross-Bedded Sandstone	X	X	X
7	Thinly-Bedded Tangential to Sigmoidal Cross-Bedded Sandstone		X	X
8	Low-Angle Tangential to Sigmoidal Cross-Bedded Sandstone			
9	Lenticular- to Wavy- and Ripple-Laminated Sandstone	X	X	X
10	Flat-Laminated to Massive Sandstone	X	X	X
11	Deformed Sandstone	X	X	X
12	Cross-Bedded Sandstone with Overturned Foresets	X	X	X
13	Intensely-Deformed Sandstone		X	X
14	Very Poorly-Sorted Paraconglomerate		X	

Facies 1. Sandy Cross-Bedded Conglomerate

Description:

This rare facies (less than 1% of total footage measured) is identified in only two places, namely at stratigraphically high levels within the Quweira Sandstone in the Al Ula area (measured sections U305 and U401 – Appendix A). Nevertheless, it is very distinctive and considered significant. The dominant constituents comprise angular granules and rounded to well-rounded pebbles and small cobbles (up to 7 cm in size) of milky-white vein quartz, concentrated at bases of foresets. Locally, angular pebble-size mud clasts also occur, interpreted as intra-formational rip-up clasts (Figure 4.1). These clasts occur in sandy matrix which ranges in grain size from coarse- to very coarse-grained sand that is moderately- to poorly-sorted. Beds of Facies 1 have sharp, erosive bases and range in thickness from 50 cm up to 150 cm. They are generally not latterly extensive. Despite its coarseness in grain size, this facies displays clear cross-bedding, with graded foresets (Figure 4.2). This facies is commonly associated with deformed sandstone facies (Facies 11, 12 and 13).

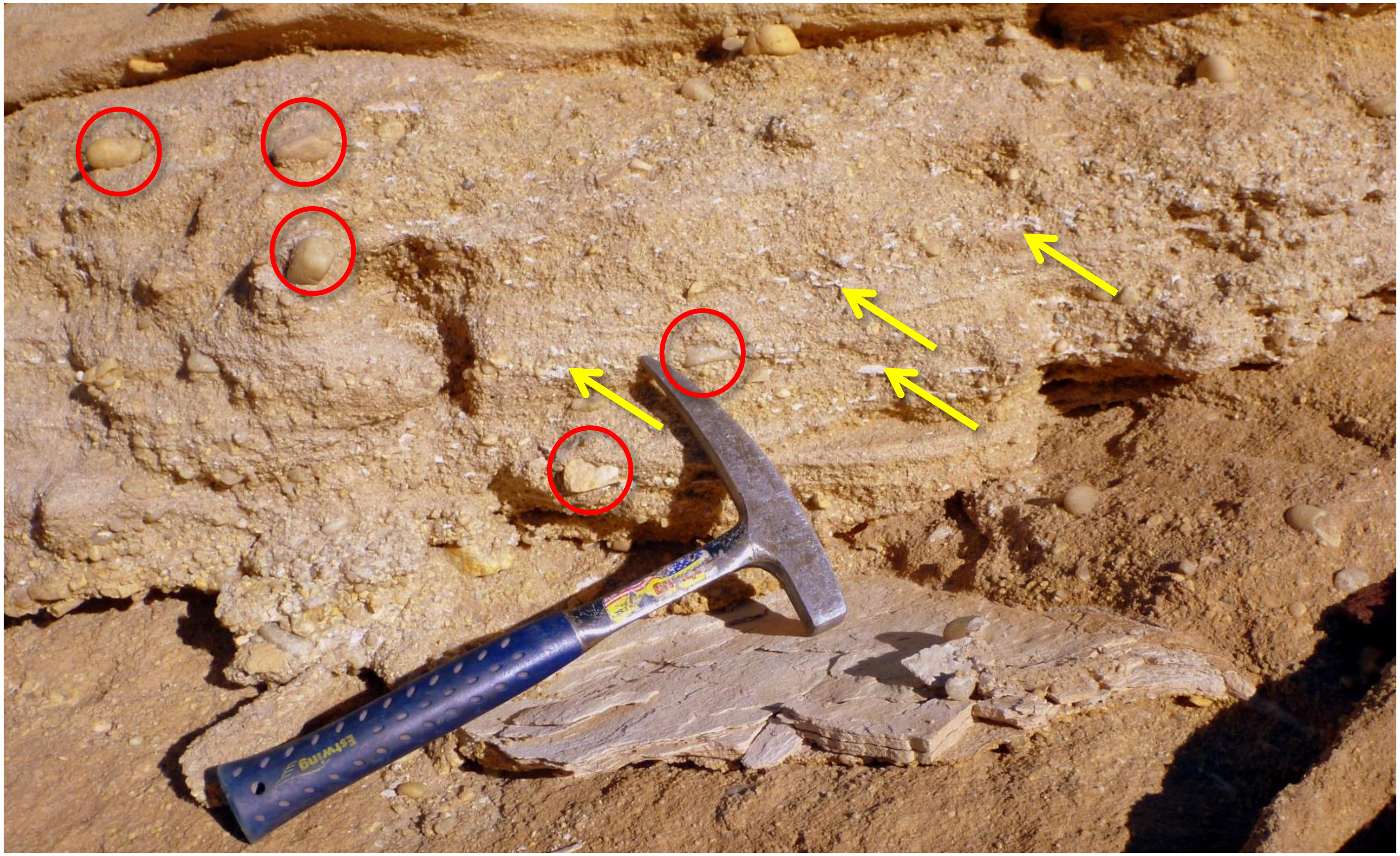


Figure 4.1: Sandy cross-bedded conglomerate showing occurrence of quartz pebbles with variable sizes and shapes (circled) as well as concentrations of mud clasts (arrows), probably generated as rip-ups from underlying fine-grained sandstone set (foreground, under the hammer head) (measured section U305 at 13.5 m – Appendix A).

Figure 4.2: Sandy cross-bedded conglomerate set showing graded foresets (arrow) (measured section U401 at ~ 29.0 m – Appendix A).

<u>Interpretation</u>:

Descriptions of Facies 1 deposits are suggestive of the base of a migrated fluvial channel, where similar deposits were referred to as “large-scale cross-bedded” units (Williams & Rust, 1969). Similar latterly-discontinuous deposits have been suggested to indicate channel bar lateral or downstream advance into adjacent anabranch channels in the Durance and Ardéche Rivers in France (Doeglas, 1962). Similarly, Smith, N. D. (1974) described low-angle cross-bedded gravel deposits of channels and bars as the product of migration of channel bars. Studies of lag deposits and clast shapes (Doeglas, 1962) have suggested that roundness of these pebbles indicates a recurring erosion and deposition of such particles, continuously affected by local turbulence effect near the channel base. Angular quartz pebbles more likely suggest a shorter transportation distance. Mud clasts observed as rip-up pebbles indicate intra-formational scouring of the top of the previous sequence of a mud flat (Reineck & Singh, 1973). Similar to rounded quartz pebbles, rounded mud clasts are possibly created by turbulence near the channel base. Association with deformed facies below is possibly a result of non-uniform confining pressures created by the deposition of Facies 1 beds, which allows sediment dewatering (Allen, 1982; Mills, 1983); see Facies 11, 12 and 13.

Facies 2. Conglomeratic Trough Cross-Bedded Sandstone

<u>Description</u>:

This is another rare facies (less than 2% of total measure footage) which is found to mark the beginning of the Quweira Sandstone deposition in the Al Ula area (in measured section U102 at ~36.0 m, U202a at 2.0 m and U302 at ~2.0 m – Appendix A), where it is rarely found higher in this unit. It is a pebble-bearing sandstone facies, with an estimated pebble: sand ratio of over 30:70 (Figure 4.3 and Figure 4.4). Sand grains are medium to very coarse in size and the gravel-sized component ranges from granule- to pebble- size clasts of angular to well-rounded quartz and mud clasts with rare feldspars and granitic clasts. The sandstones display trough cross-bedded sets with thicknesses ranging from 30-60 cm and up to 100 cm. Concentrations of pebbles occur at bases of sets and foresets. Scouring is abundant in this facies. Scour surfaces are generally shallow (cm scale), and are found latterly discontinuous (in several meters). Similar to Facies 1, this facies also appears to be associated with deformed facies (see Facies 11, 12 and 13).

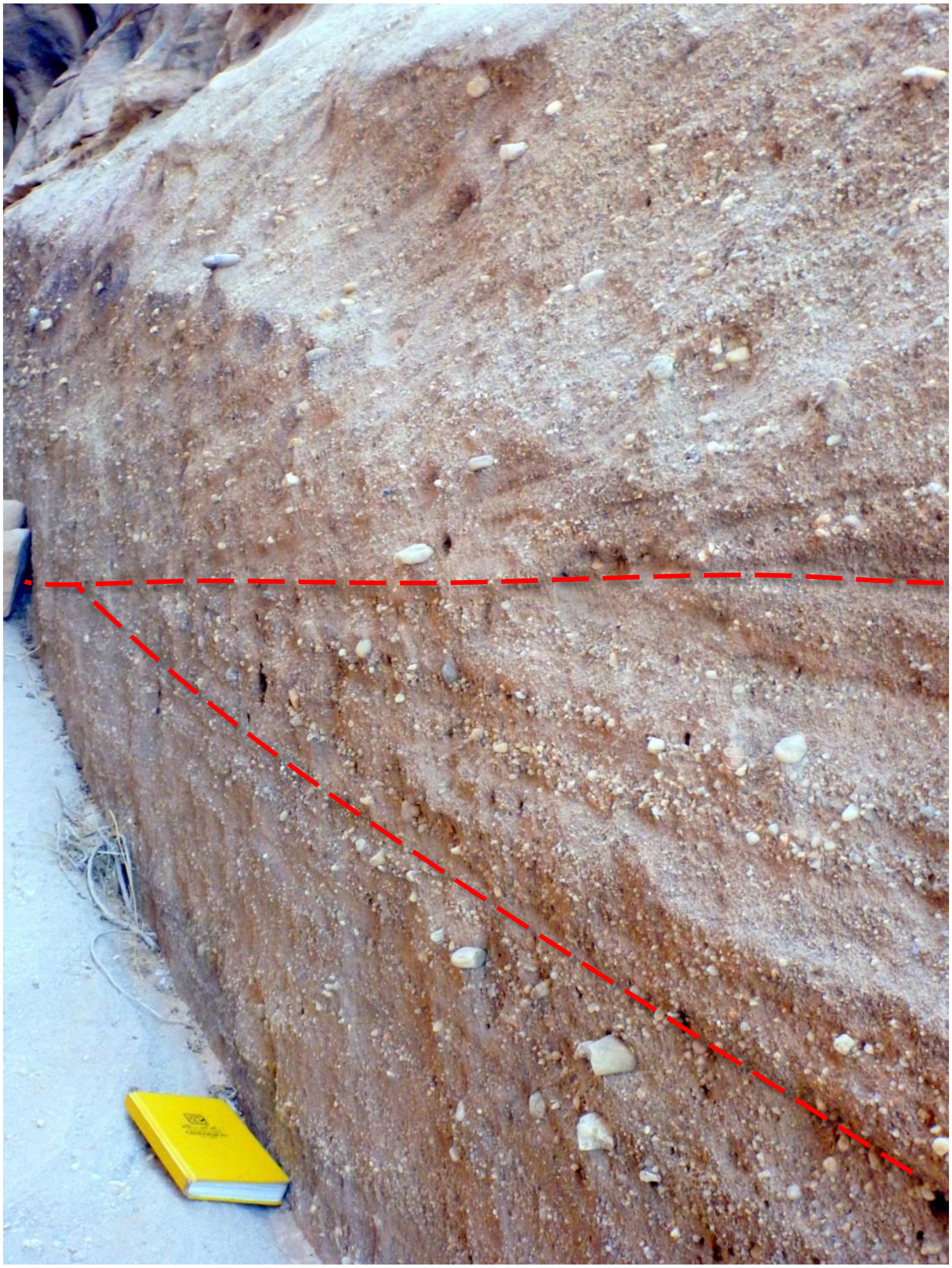


Figure 4.3: Conglomeratic trough cross-bedded sandstone sets showing concentrations of pebbles at bases of foresets (dashed lines highlight bases of sets) in Mada'in Saleh area – U2.

Figure 4.4: Conglomeratic trough cross-bedded sandstone sets show variable pebble sizes in a moderately-sorted framework (Measured Section U202a – Ad' Diwan section in Mada'in Saleh).

<u>Interpretation</u>:

Facies 2 deposits are also indicative of migrating fluvial channel bars, with possible alternating gravel and sand-framework, as observed in Facies 1; see Smith, N. D. (1974). This interpretation is also suggested by recurring scouring at bases of sets in places (Williams & Rust, 1969). Trough cross-bedding is indicative of fluvial channel-deposition (Reineck & Singh, 1973). Generally rounded pebbles of quartz, mud clasts and rare feldspars and granitic clasts are maybe indicative of a variable local to distant source. Pebble roundness is the product of the continuous effect of turbulence and abrasion at the base of channel that possibly might have migrated multiple times (Doeglas, 1962). Deposits found this low in a fining-upward channel bar sequence may demonstrate lateral continuity, where boundaries between different sets are hard to identify due to scouring (Doeglas, 1962; Bristow, 1993b). Similar to Facies 1, association with underlying deformed sandstone deposits is possibly a result of non-uniform confining pressures created by the deposition of Facies 2 beds, which allows sediment dewatering (Allen, 1982; Mills, 1983); see Facies 11, 12 and 13.

Facies 3. Pebbly Trough Cross-Bedded Sandstone

<u>Description</u>:

One of the most-commonly occurring facies in the succession (more than 15% of total measured footage), deposits of Facies 3 are found through the succession in the Al Ula are, but are limited to stratigraphically higher in the Quweira Sandstone in the Tabuk area. This is also a pebble-bearing sandstone facies, with an estimated pebble: sand ratio of equal to or less than 30:70. Grain size of the sandstones in this facies ranges between medium and coarse sand, with moderately- to poorly-sorted and sub-angular to sub-rounded grains. Within the sandstone beds, grain size commonly shows fining-upward trends. Thicknesses of cross-bedded sets are in the range between 10-40 cm and rarely up to 75 cm, and widths are generally between 2-5 m, with extreme examples of up to 10 m-wide sets. Repeated truncation and basal scouring are characteristic features of this facies. Pebbles are mostly concentrated at the bases of foresets (Figure 4.5), but they are also less commonly found concentrated at bases of sets, bases of beds as well as randomly distributed within sets. Pebbles mostly consist of angular to rounded and well-rounded quartz (up to 6 cm in size). Mud clasts are also observed in abundance at bases of beds, particularly in the Upper Siq Sandstone in the Al Ula area (Figure 4.6). Granitic clasts and feldspars are only rarely observed in this facies throughout the succession. Scour surfaces commonly show lag concentrations of pebble-size quartz, feldspars, mud clasts and granitic rock fragments.

Figure 4.5: Pebbly trough cross-bedded sets showing concentrations of coarser sand- to pebble-size quartz at the base of the set and bases of foresets (measured section U401 at 19.0 m – Appendix A).

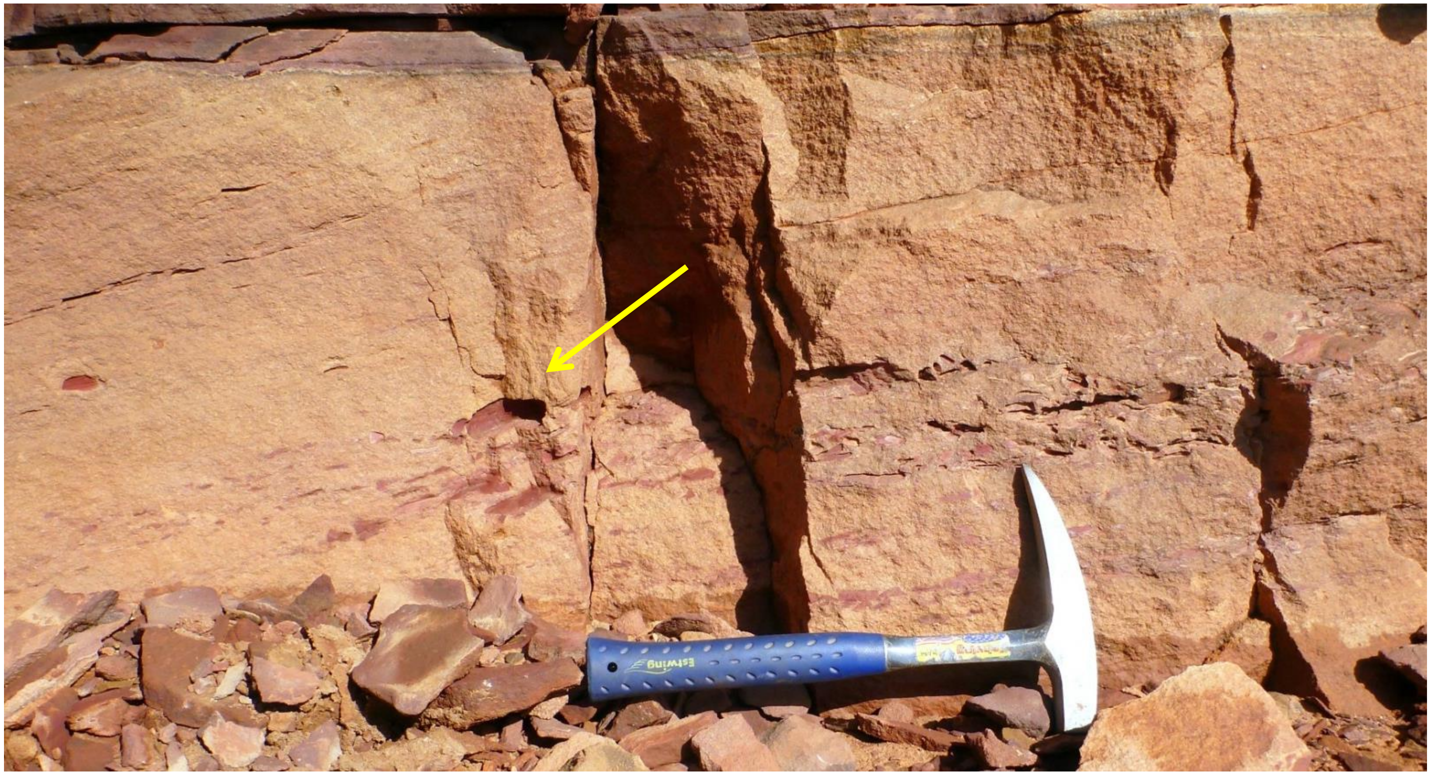


Figure 4.6: Pebbly trough cross-bedded sandstone set with concentration of mud-clast pebbles at bases of foresets (arrow) in the Upper Siq Sandstone in the Al Ula area (measured section U301 at 24.5m – Appendix A).

Interpretation:

Bedding that displays Facies 3 sandstones has been interpreted as sandy fluvial braid bar deposits (Coleman, 1969). Marked as both zones A and B in Coleman's interpretation, observations recorded in the Brahmaputra River braided streams show thick sets and relatively large ripples as well. These observations are indicative of actively migrating channel bars. Studies in the South Saskatchewan River, Canada, support these interpretations and further indicate these in-channel deposits to be associated with lag deposits in fining-upward sequences (Cant & Walker, 1978). Deposits of Facies 3 are interpreted to be analogues to Facies A and B in Cant and Walker (1976) Devonian Battery Point Formation model; poorly-defined and well-defined trough cross-bedded sandstones. Presence of gravels and grading of foresets is observed in similar successions and is interpreted to represent variation in proximal and more distal setting in a migrating braided channel (Miall, 1977; 1978). Presence of rounded quartz and mud clast pebbles at bases of foresets in Facies 3 is the product of turbulent effect at channel bases (Doeglas, 1962), and it suggests bar migration between local and more proximal setting. Rounded mud pebbles can possibly be the product of reworked slumped blocks of lag deposits (Reineck & Singh, 1973). Sandstone units where Facies 3 is abundant and scouring seems to be recurring is possibly indicative of a fluctuating discharge (Bristow, 1993b). Deformed facies associated with these deposits, in addition to recurring truncations and scours, is commonly observed within bedding similar to Facies 3 (see Facies 11).

Facies 4. Trough Cross-Bedded Sandstone

<u>Description</u>:

The most abundant facies in the studied succession (close to 40% of total measured footage), deposits of this trough cross-bedded sandstone facies are found in most of the sandstone units examined in the Al Ula and Tabuk areas. Sand grain size is predominantly medium- to coarse-grained and is only rarely fine-grained. The sandstones are moderately- to poorly-sorted, and the grains most commonly range from sub-angular to sub-rounded. Trough cross-bedded sets vary in thickness within the range between <10-40 cm and locally up to 75 cm, with widths varying from less than one meter up to 7 m (Figure 4.7). Grading is observed within foresets. Rare gravel-size quartz and mud clasts are generally found at bases of foresets. Bedding truncations are widespread, and the cross-bedding shows common evidence of overturning and failure (see Facies 11 and 12). Generally, paleocurrent measurements do not exceed the range of 30° in current direction between trough cross-bedded sets (Figure 4.8). This range in paleocurrent direction can be slightly higher between sets thinner than 10 cm. Scour surfaces of limited extent commonly display concentrations of pebble-size lag deposits, including rounded quartz and locally mud clasts.

Figure 4.7: Trough cross-bedded sandstone set that is relatively wide (base of set highlighted; width up to 6 m) (measured section T101 – Ash' Shiq at ~ 3.0 m – Appendix A).

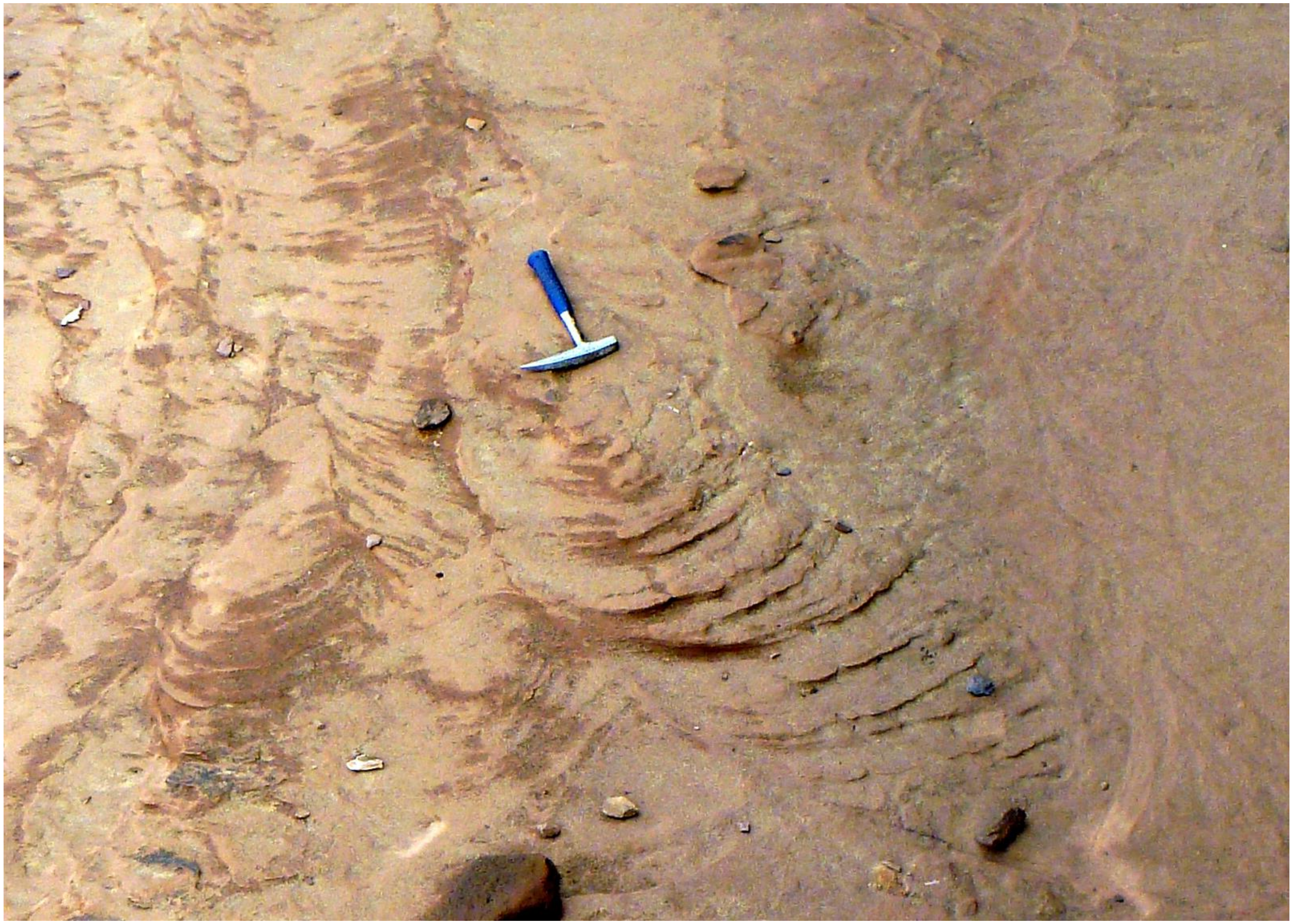


Figure 4.8: Thinly-bedded trough cross-bedded sandstone sets show changes in paleocurrent directions (measured section T101 – Ash' Shiq at ~23.5 m – Appendix A).

<u>Interpretation</u>:

Similar to Facies 3 deposits, latterly-continuous Facies 4 sandstones are interpreted as observed in previous work as in-channel deposits that are actively migrating, as reflected by the abundance of truncations and scouring (Coleman, 1969; Cant & Walker, 1976; 1978; Miall, 1992). Rare presence of gravels has been recorded in previous work to indicate minor variation in proximality (Miall, 1977; 1978). Lack of reactivation surfaces and mud drapes in parts of sequences of these deposits is likely indicative of a continuous discharge with minor seasonal fluctuations (Bristow, 1993b). Variations in paleocurrent measurements among sets in a single bed is suggested not to be critical in this part of the setting, since the overall mean vector commonly indicate the channel current direction (Coleman, 1969).

Facies 5. Planar Tabular Cross-Bedded Sandstone

<u>Description</u>:

These generally comprise thick sets of planar-tabular cross-bedded sandstone that are found in isolation throughout studied sedimentary succession (less than 7% of total measured section in both study areas). It has limited occurrence in the Middle Siq Sandstone and the middle part of the Quweira Sandstone in the Al Ula area, where it is commonly deformed in the Saq Sandstone. It also occurs in the Quweira and Saq Sandstones in the Tabuk area. It is the dominating facies in the latter unit (Figure 4.9). In Facies 5 sandstones, the grains are generally medium to coarse sand size, moderately- to poorly-sorted, and sub-angular to sub-rounded. Commonly found as isolated sets throughout the succession (except in the Saq Sandstone in the Tabuk area), the foresets in one sandstone bed rarely show discordance and back-flow ripple features (measured section U101 at 19.0 m – Appendix A) (Figure 4.10). Set thickness ranges between 40-150 cm. Rare concentrations of rounded quartz pebbles (up to 4 cm in size) are seen at bases of foresets. Rare scour surfaces show concentrations of rounded quartz pebbles. Deposits of this facies also display evidence of deformation in places (see Facies 11, 12 and 13).

Figure 4.9: Planar tabular cross-bedded sets that shows discordance (dashed lines) and back-flow ripple structures (circled) (measured section U101 at 19.0 m – Appendix A).

Figure 4.10: Planar tabular cross-bedded sandstone sets of the Saq Sandstone in the Tabuk area (measured section T105 at 22.0 m – Appendix A).

Interpretation:

These sandstones are interpreted as sand flat deposits in fluvial braided channels. Large sets of planar tabular cross-beds are indicative of cross channel bars, similar to observations in the Saskatchewan River in Canada (Cant & Walker, 1978; Walker & Cant, 1984). In a depositional setting that is characterized by shallow river water, as observed in Platte River, planar tabular cross-bedded sets are found dominant (Smith, N. D., 1970). Therefore, it can be suggested that due to limited distribution of this facies relative to the various trough cross-bedded sandstones, the overall depositional setting is dominated by fluvial in-channel deposits in a relatively deep water fluvial system. This is supported by the suggestion that such facies is indicative of an overall lower current velocity (Ashley, 1990). Isolated large-set distribution of these sandstones suggests a continuous high-energy discharge, and where these "small planar tabular" cross-bedded sets are abundant, as observed in the Saq Sandstone in the Tabuk area, is probably suggesting a more distal and lower-energy depositional setting (Cant & Walker, 1976; 1978; Walker & Cant, 1984; Bristow, 1993b). Rarely-observed discordance (Figure 4.9) is found common in similar deposits in the Ganga River (Singh, 1977), and is representative of paleocurrent divergence to channel flow (Walker & Cant, 1984). Rare back-flow ripple structures are indicative of local turbulent effect in the zone of backflow (Reineck & Singh, 1973). Local concentrations of pebbles are possibly indicative of temporary higher discharge, and minor deformation is possibly related to fluid-flow within sediments (Allen, 1982).

Facies 6. Tangential to Sigmoidal Cross-Bedded Sandstone

Description:

Less abundant facies in the succession (only ~10% of total measured footage), tangential and sigmoidal cross-bedded sandstone sets were lumped in one facies because these sets commonly show these two types of sedimentary structures in association with each other in different parts of the succession. In several examples, it appears that some tangential cross-bedded sets are the product of erosion of topsets of sigmoidal cross-bedded sets (see also Facies 7). This facies is found in all sandstone units, except for the Upper Siq Sandstone in the Al Ula area. It dominates the latter sandstone unit in the Tabuk area, however. Set thicknesses vary from 20-50 cm in Al Ula (Figure 4.11 and Figure 4.12) and are up to 80 cm in the Tabuk area, where sets are also likely to be more laterally-continuous (Figure 4.13). Sandstones show graded foresets, and grains are medium- to coarse-grained, well- to moderately-sorted and sub-angular to well-rounded. Quartz pebbles are locally observed concentrated at bases of foresets and toesets. In limited occurrences throughout the succession, foresets appear bundled in various sizes (Figure 4.14) and others show double-clay drapes (Figure 4.15). As it has been noted in other cross-bedded sandstone facies, tangential to sigmoidal cross-bedded sets also display degrees of internal deformation that ranges from a minor disruption of lamination to a complete deformation of the bed (see Facies 11, 12 and 13).

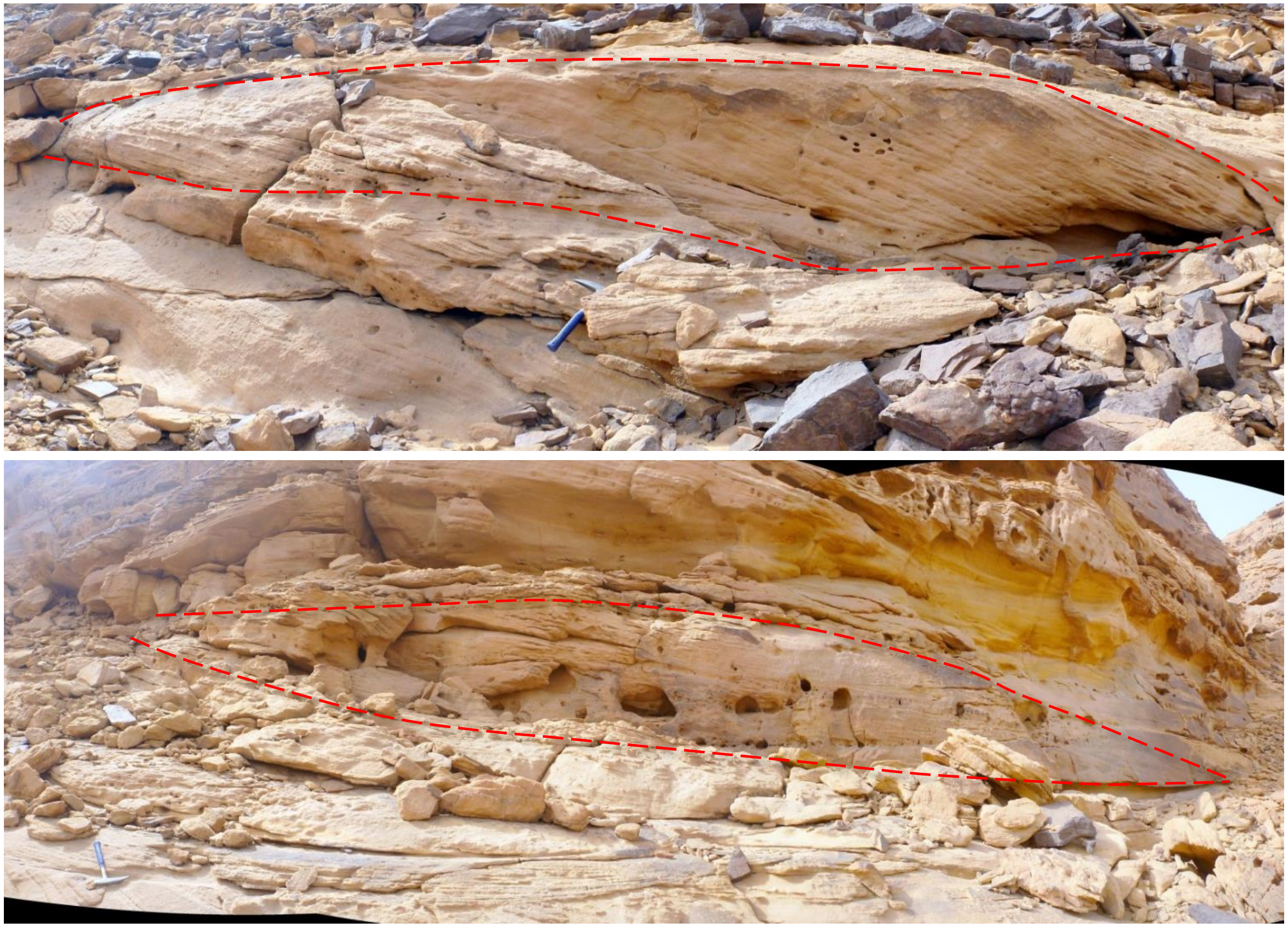


Figure 4.11: Two examples of sigmoidal cross-bedded sandstone sets on top of trough cross-bedded and thinly-bedded sigmoidal cross-bedded sandstone sets near the base of the Quweira Sandstone in the Al Ula area (measured section U102 at 39.5 m - Appendix A, and the top of the same section).

Figure 4.12: Tangential to sigmoidal cross-bedded sandstone set (possibly shows bundling of foresets) in the Saq Sandstone in the Al Ula area (measured section U502b at 14.0 m – Appendix A).

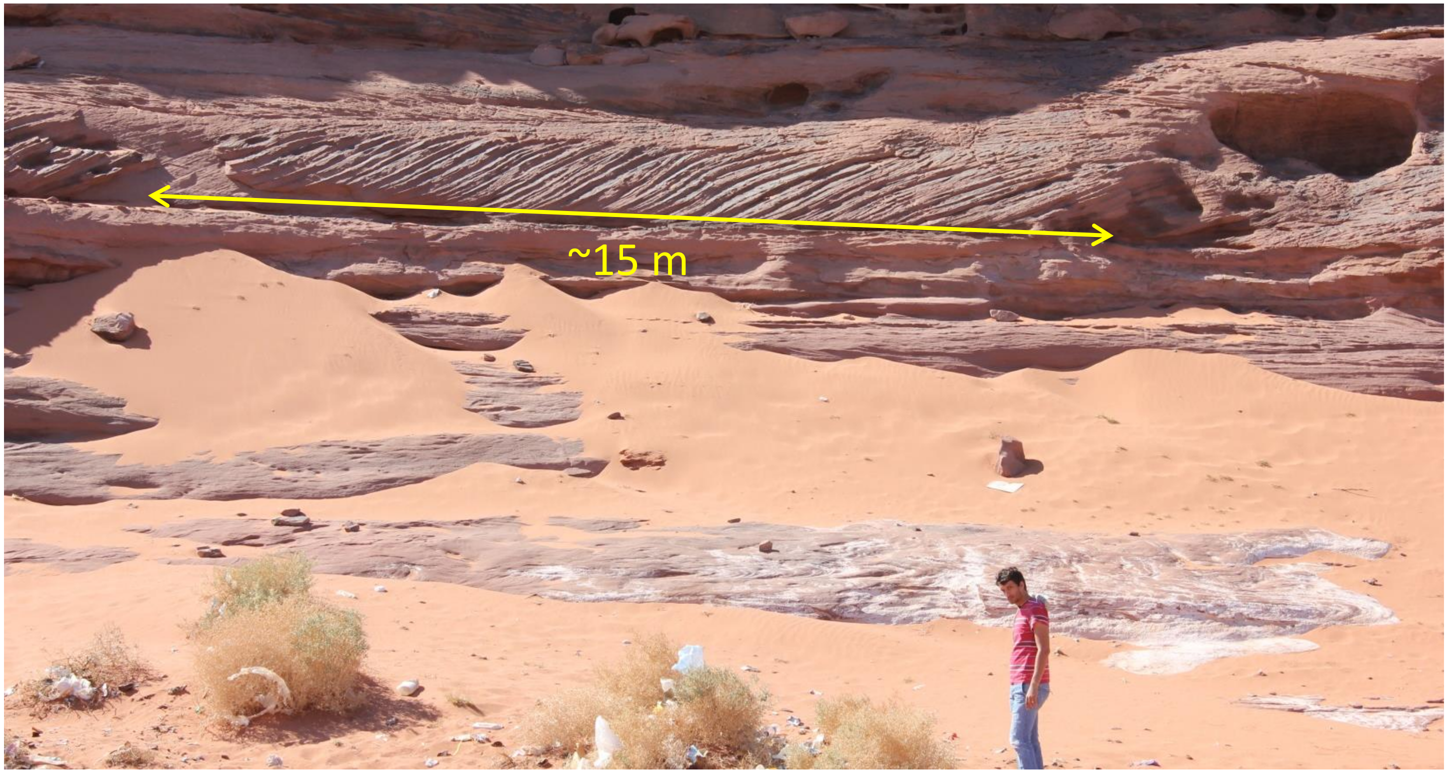


Figure 4.13: Sigmoidal cross-bedded sandstone set showing high degree of lateral continuity. Similar examples were observed in different parts of the succession, but are significantly more abundant in the Tabuk area (near Ash' Shegri – Tabuk area).

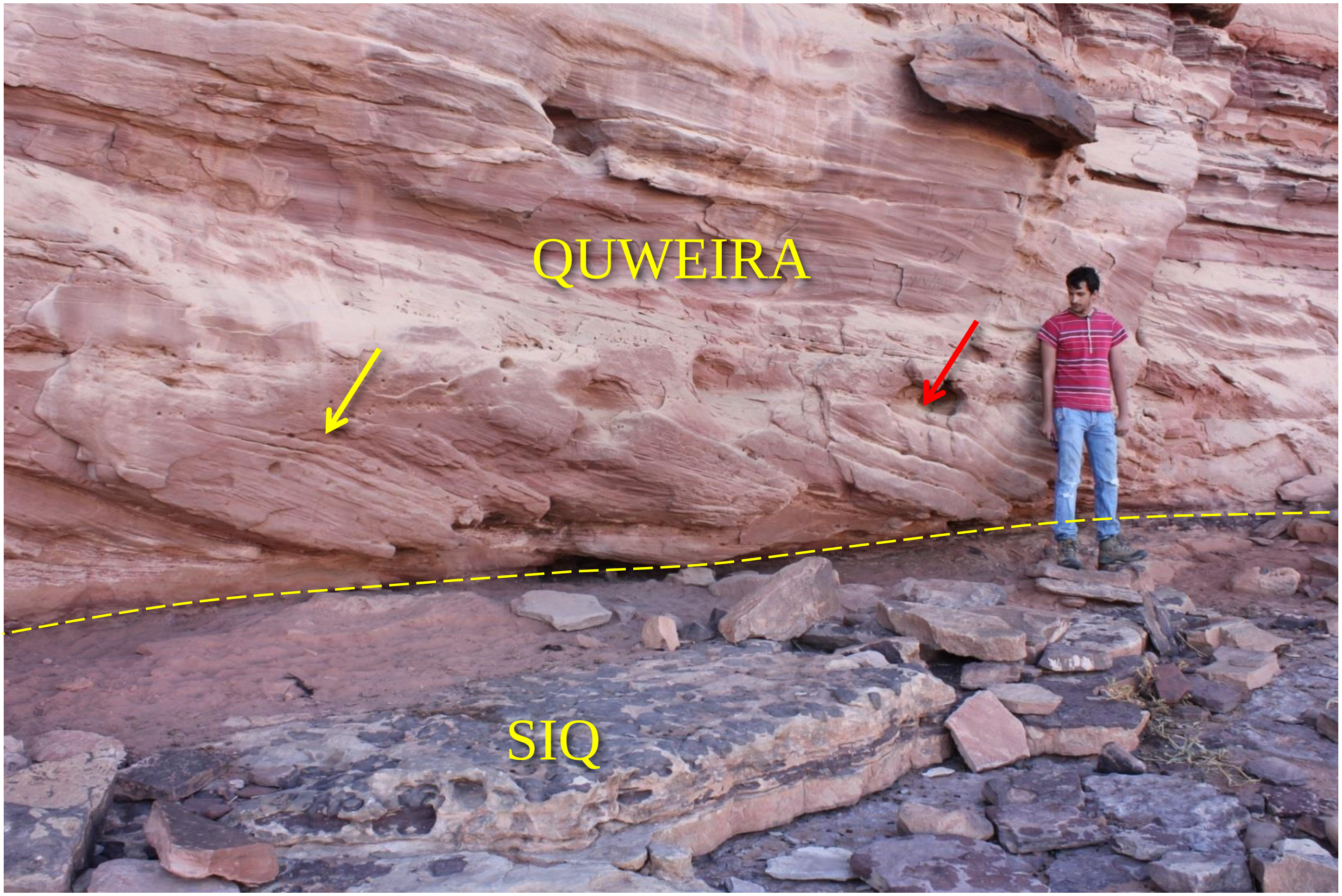


Figure 4.14: Bundled-foresets in a sigmoidal cross-bedded sandstone set with great variation in foreset thicknesses (arrows), which abruptly overlie the conformable contact between the Siq and the Quweira Sandstones in the Tabuk area (measured section T101 at ~16.0 m – Appendix A).

Figure 4.15 Sigmoidal cross-bedded sandstone set showing common occurrences of "double-clay drapes" (scale is 15 cm) (measured section T101, marking the base of the Quweira Sandstone in the Tabuk area at 16.5 m – Appendix A).

<u>Interpretation</u>:

Sandstones of this facies are interpreted as the product of the reworking by tidal currents within an estuarine setting (Dalrymple, 1992). Observations in the English Channel (Howarth, 1982), The Cobequid Bay-Salmon River (Dalrymple et al., 1990; Dalrymple et al., 1991) and The Brahmaputra River (Bristow, 1993a), have described different examples of sandy successions of sigmoidal cross-bedded sets that were interpreted to indicate deposition of tidal sand bars and tidal sand waves in a subtidal to generally low to intermediate intertidal depositional setting (Dalrymple, 1992). These deposits possibly correspond to the middle unit of Beek and Koster (1972) tidal sand flat model. Their model is characterized by an alternating large-scale and small-scale (Facies 7?) cross-bedding, indicative of influence of tidal currents in the Oude Maas River in The Netherlands. Concentrations of pebbles at bases of foresets of tangential cross-bedded sets corresponds to the lower unit of this sequence model (Beek & Koster, 1972). Recurring erosional surfaces at the topsets, and the conversion to tangential cross-bedding, is indicative of migrating dunes in a tidal sand wave as a result of increased tidal current (velocity) – see compound cross-bedding (Allen, 1980; Dalrymple, 1984). Lateral continuity is indicative of a wide tidal range (Reineck & Singh, 1973). Bundled foresets, also known as tidal bundling, is a product of reworking of sediments through the complete tidal cycle, where thick and thin bundles form during spring and neap tides, respectively. Accumulations of (double) mud drapes occur during neap tides or slack-water periods (Dalrymple, 1992). Deformation of such sandstones is caused by different deformation process, mostly involving liquefaction (Allen, 1982; Mills, 1983) – see

Facies 11, 12, and 13. Further references that describe such processes include Nio and Yang (1991) and Martinius et al. (2011).

Facies 7. Thinly-Bedded Tangential to Sigmoidal Cross-Bedded Sandstone

Description:

This facies represents about 6% of total measure footage in both the Al Ula and Tabuk areas. Similar to Facies 6, these deposits differ only in the thicknesses of sets (rarely greater than 10 cm) (Figure 4.16). It is found in almost all parts of the studied succession except for the Upper Siq Sandstone in the Al Ula area. Sand grains in Facies 7 are mostly medium-sized, generally moderately- to well-sorted and sub-angular to well-rounded. Sets of this facies are most commonly found near the top of cycles (example in measured section U201 in the Al Khuraimat section – Appendix A) and in places are overlain by lower-energy, finer-grained depositional facies (Facies 9 and 10). Elsewhere, they are scoured into by coarser-grained sandstone facies deposits (see measured section U101 – Appendix A). Scouring observed in this facies has resulted in the conversion of sigmoidal cross-bedding into tangential cross-bedding (Figure 4.17). Sets also show bundled foresets and deformed sets in places.

Figure 4.16: Thinly-bedded tangential to sigmoidal cross-bedded sandstone sets that are about 10 cm thick in the middle part of the Quweira Sandstone in the Al Ula area, showing evidence of limited scouring (one-meter stick for scale) (measured section U201 in the Al Khuraimat section, Mada'in Saleh at 15.0 m – Appendix A).

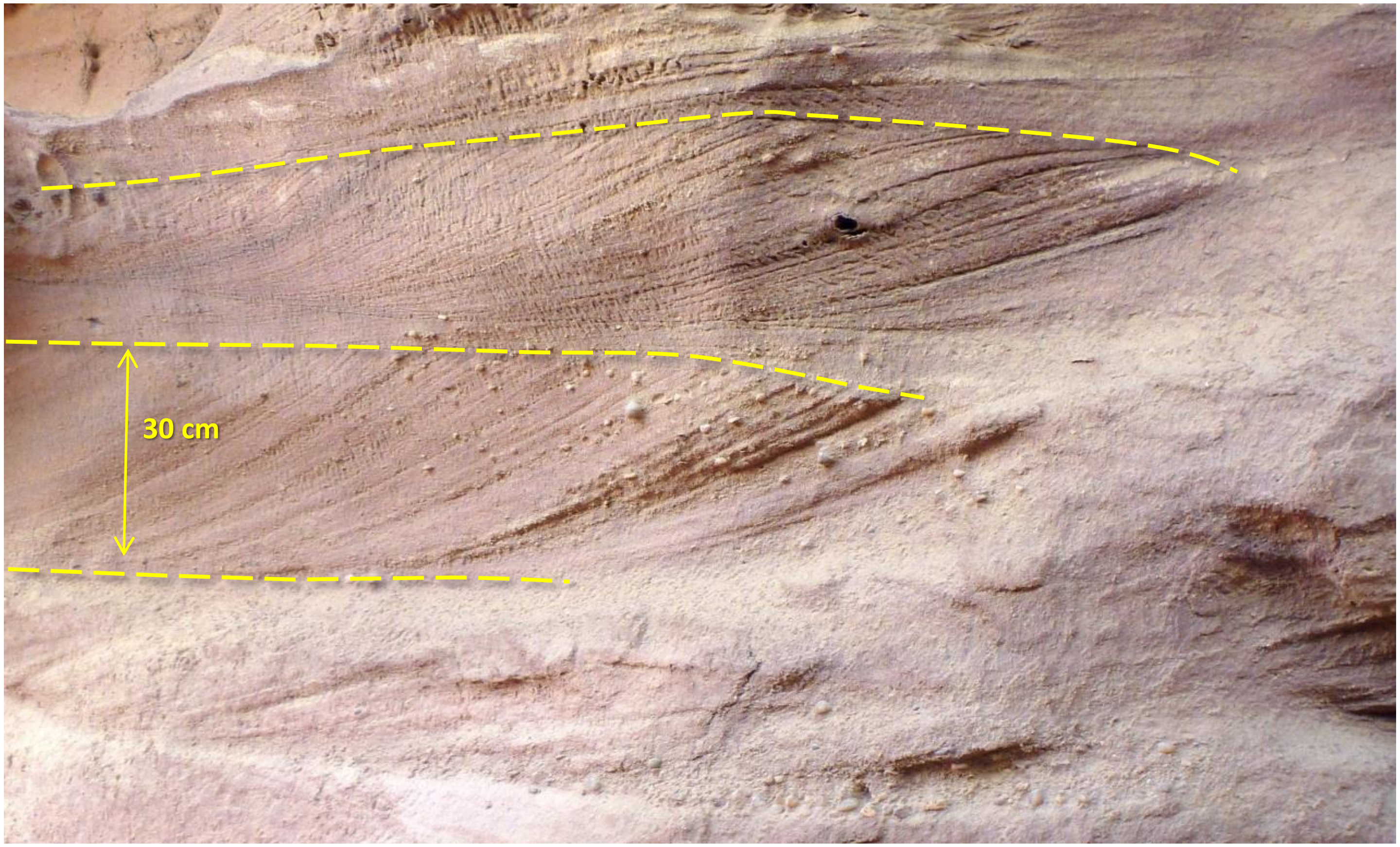


Figure 4.17: Thinly-bedded sigmoidal cross-bedded sets developed by the scouring of their topsets into thinly-bedded tangential cross-bedded sandstone sets (bases of sets highlighted) (measured section U101 at 2.0 m – Appendix A).

Interpretation:

Facies 7 is a thinner-bedded version of tangential to sigmoidal cross-bedded sandstone (Facies 6), reflective of the fining-upward nature of successions observed in tidal sand models (Beek & Koster, 1972; Dalrymple, 1992). Scours observed on top of these sandstones are possibly indicative of migrating tidal channels (Cant & Walker, 1978). Similar features have already been interpreted in Facies 6.

Facies 8. Low-Angle Tangential to Sigmoidal Cross-Bedded Sandstone

Description:

This rare facies (less than 1% of total measured footage) is limited to the Middle Siq Sandstone and one occurrence higher in the Quweira Sandstone in the Al Ula area. Generally 10-40 cm thick, silty to argillaceous, fine- to medium-grained sandstone, in which the grains are well- to moderately-sorted and sub- to well-rounded, these sets are characterized by low-angle (estimated <15°) tangential cross-bedded sets (Figure 4.18) that locally show sigmoids at topsets. They also contain significantly higher mud content, compared to Facies 6 and 7, where mud drapes commonly form in the lower parts of foresets (Figure 4.19). Facies 8 shows abundance of relatively deeper scours (cm- to dm-scale) than the previous two facies described (Figure 4.20, Figure 4.21 and Figure 4.22).

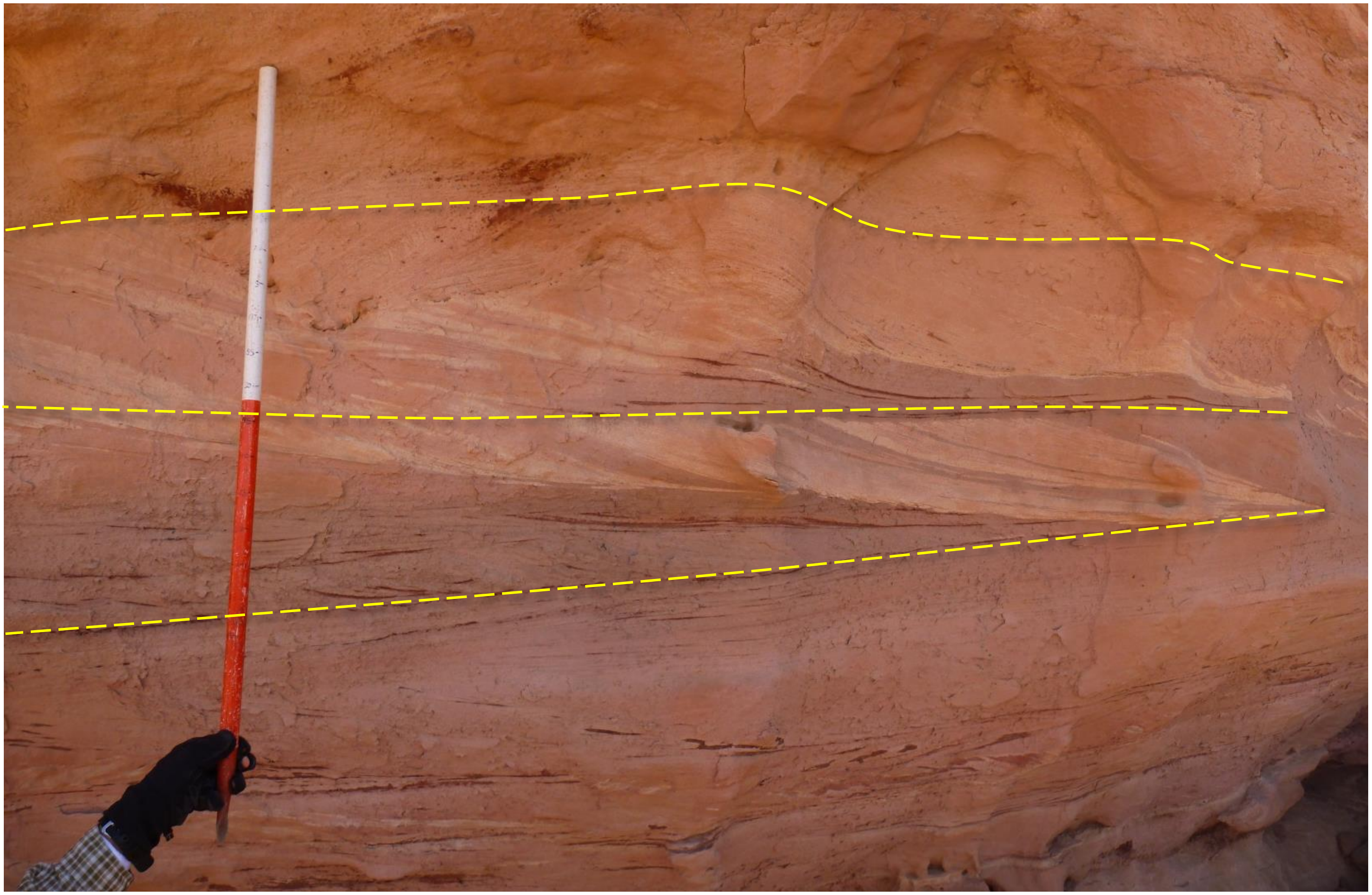


Figure 4.18: Multiple low-angle tangential cross-bedded sandstone sets (bases of sets highlighted) with noticeable mud drapes in the lower parts of foresets (one-meter stick for scale) (the Middle Siq Sandstone in measured section U101 at 57.0 m – Appendix A).

Figure 4.19: Multiple sets of low-angle tangential to sigmoidal cross-bedded sandstone sets with discontinuous mud drapes dominating the lower parts of foresets (the Middle Siq Sandstone in U1 area in the Al Ula area).

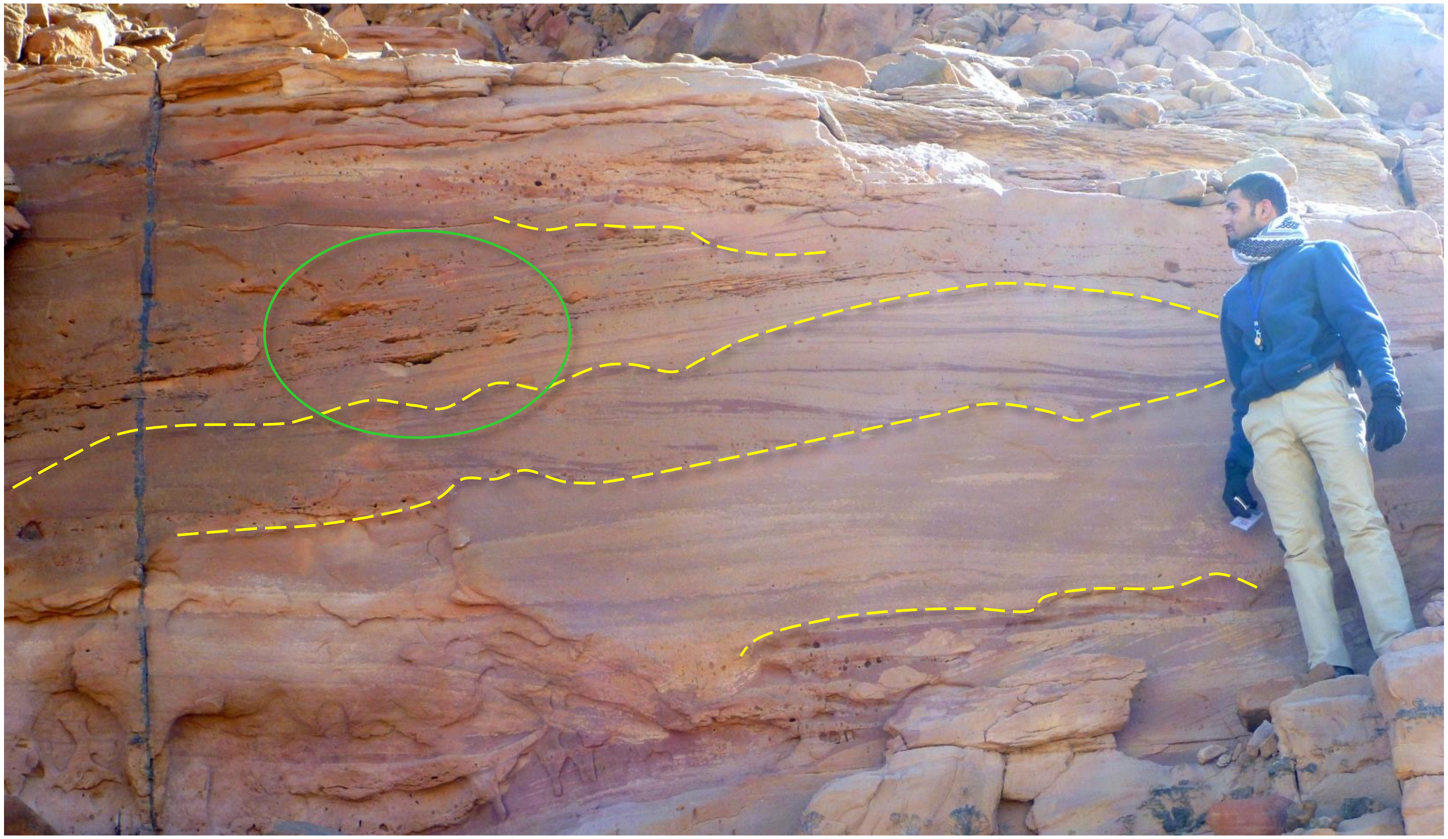


Figure 4.20: Multiple sets of low-angle tangential to sigmoidal cross-bedded sandstone separated by common scour surfaces (lines). Green circle highlights location of Figure 4.21 (the Middle Siq Sandstone in measured section U101 at 42.0 m – Appendix A).

Figure 4.21: Multiple sets of cm-scale low-angle tangential to sigmoidal cross-bedded sandstone with variable scouring (lines highlight bases of sets). Sets are overlain by Facies 9; Ripple-Laminated Sandstone bed with abundance of mud clasts (the Middle Siq Sandstone in measured section U101 at 42.0 m – Appendix A).

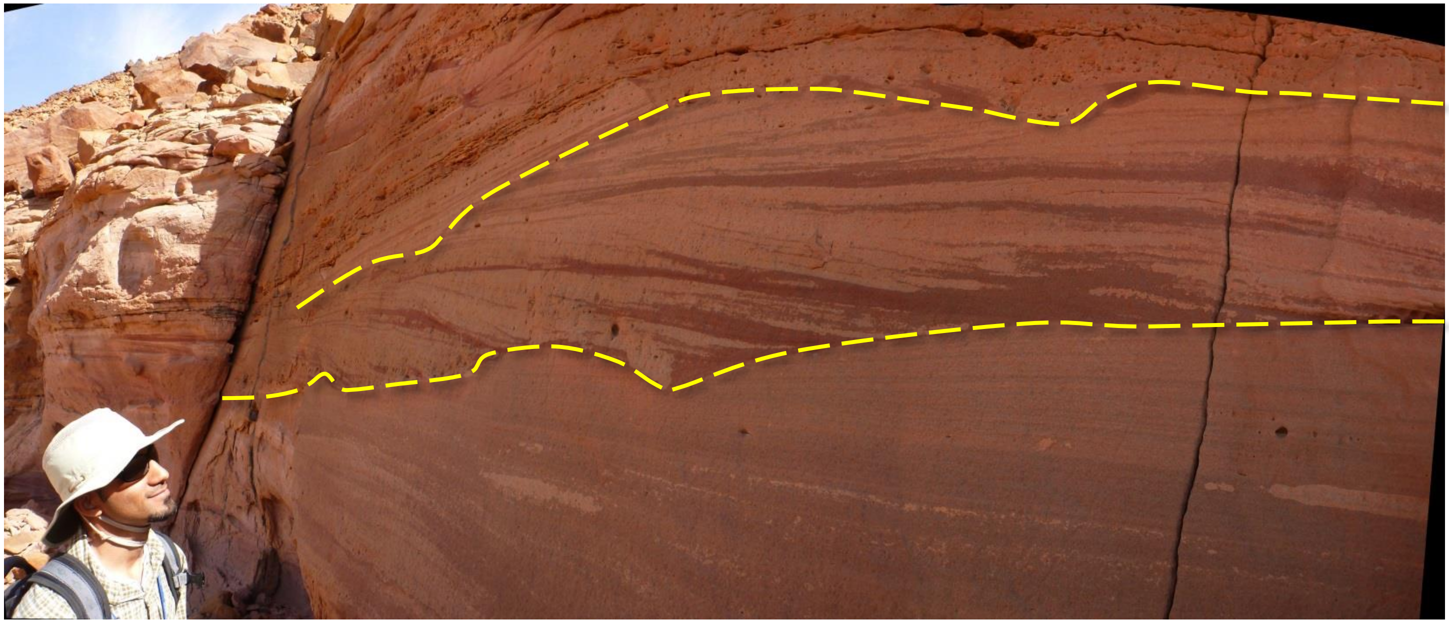


Figure 4.22: Multiple sets of low-angle tangential to sigmoidal cross-bedded sandstone with dm-scale scouring (lines highlight scour surface) (the Middle Siq Sandstone in measured section U101 at 57.0 m – Appendix A).

<u>Interpretation</u>:

Presenting a variation of sigmoidal to tangential cross-bedded sandstone (Facies 6), low-angle foresets and recurring scours are the product of an increase of subordinate tidal current energy during ebb tide (Dalrymple, 1992), possibly during times of low-energy fluvial deposition. Relative increase in mud content in the form of mud pellets (progressively into mud flats – see Facies 10) is possibly indicative of a shift into a higher-level intertidal depositional setting. This may also suggest variable tidal energy (in tidal cycles) with relatively low-energy fluvial input.

Facies 9. Lenticular- to Wavy- and Ripple-Laminated Sandstone

<u>Description</u>:

These finer-grained deposits are observed at tops of cycles and beds when preserved (see top of measured section U305 for example – Appendix A). They account for around 3% of total measured footage, and generally occur locally near or at tops of cycles throughout the succession in the Al Ula area (except for the Lower Siq Sandstone; measured Section U101 – Appendix A) and the Tabuk area. Silty to argillaceous in places, grain size is generally very fine- to fine-grained sand. Grains are well- to moderately-sorted and sub- to well-rounded. This facies is considered heterolithic, with mud content obscured due to weathering (Figure 4.23). Facies 9 displays various, but related sedimentary structures that include ripple-laminated sandstones and discontinuous lenticular- (rare flaser-) laminated and continuous wavy-laminated sandstones (Figure 4.23) in fining-upward trends when detected. They display evidence of bioturbation in places that locally occurs as discrete trace fossils, which include *Cruziana* (Figure 4.24).

Figure 4.23: Very fine-grained, ripple-laminated sandstone, showing the effect of weathering on eroded mud content (top of section U305; higher in the Quweira Sandstone; at 58.5 m – Appendix A).

Figure 4.24: Facies 9 sandstones in the Saq Sandstone unit showing a *Cruziana* trace fossil (top of section U502 at 18.5 m – Appendix A).

Interpretation:

These sequences are interpreted to have been deposited on top of channel bars, at times when the channel ceased migration, as observed in channel bars in the Brahmaputra River (Coleman, 1969). Such ripples have also been recorded on top of silt-dominated parts of channel bar sequences (Miall, 1978). Mm-scale ripples observed in Facies 9 are also indicative of subaqueous deposition on top of tidal sand flats (Singh & Wunderlich, 1978). Discontinuous, heterolithic lenticular- (and flaser-) laminated sequences are indicative of increased mud content during deposition in a subtidal and intertidal zones during slack water phase (Van Straaten, 1954; Reineck et al., 1968). The relative paucity of sequences of Facies 9 (and Facies 10) is indicative of a continuous channel migration in a fluvial-tidal mixed setting. They are generally deposited during the falling stage related to channel migration (Smith, N. D., 1974). Soft-ground ichnofacies, including *Cruziana* are characteristic of littoral and sublittoral estuary and tidal flat setting between minimum and maximum wave base in upper offshore (Pemberton et al., 1992), are possibly indicative of times of marine transgression in a drowned estuarine-river valley (Weil, 1977). Deposition of such facies and other tidally-influenced facies within tidal sand flats has been indicated in previous work by Dalrymple (1992), where a 3-D depositional model illustrates this deposition in subtidal to intertidal and supratidal environments (Figure 4.25).

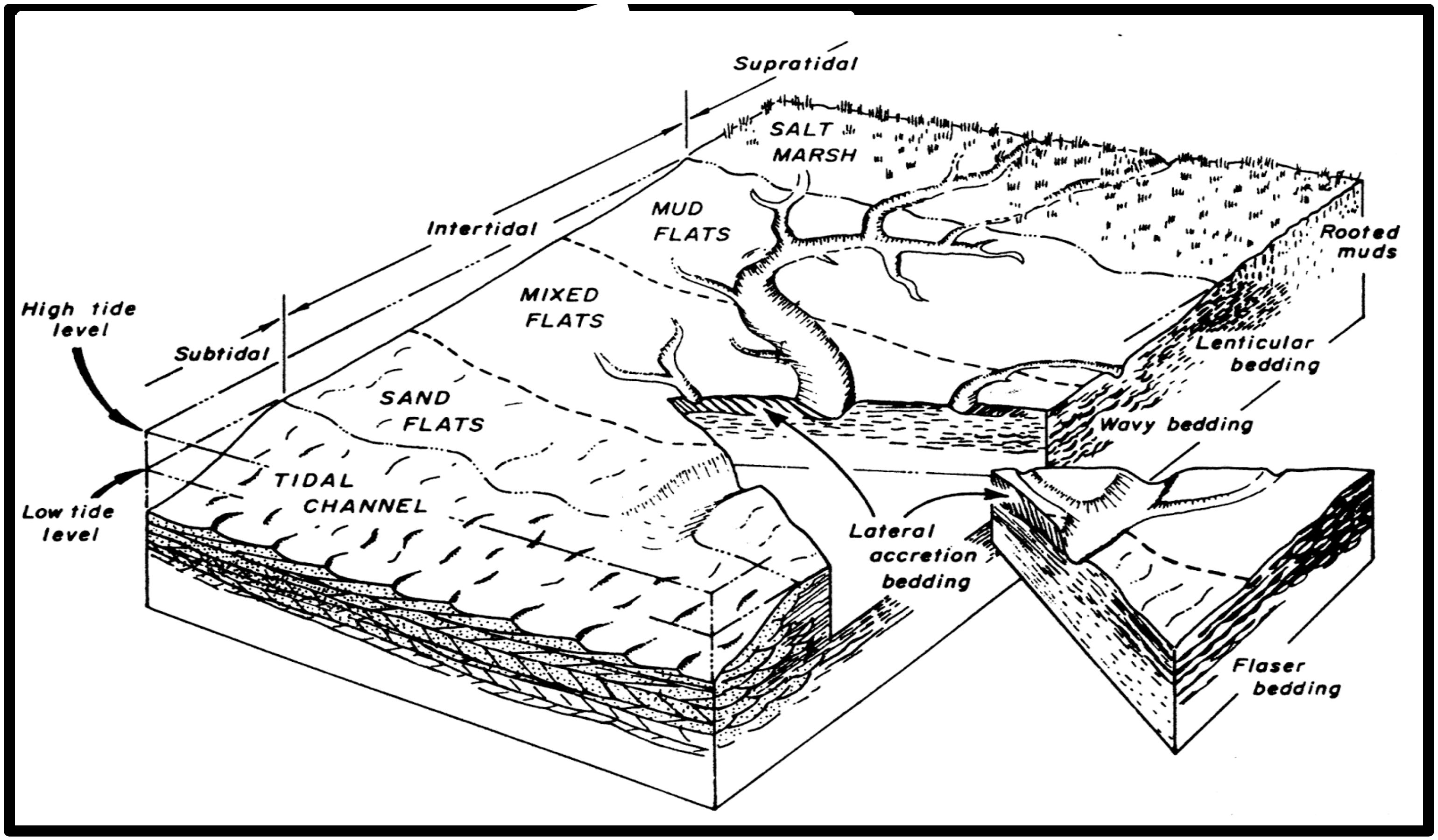


Figure 4.25: 3-D model of tidal sand flat deposition in subtidal to supratidal depositional setting (modified after Dalrymple (1992)).

Facies 10. Flat-Laminated to Massive Sandstone

Description:

Facies 10 occupies less than 8% of the succession in the Al Ula area and is limited to parts of the Upper Siq Sandstone and the Saq Sandstone in the Tabuk area. Deposits show mm-scale continuous (to discontinuous in places) low-angle to flat-laminated and massive sandstone (Figure 4.26). Silty to argillaceous in places, grain-sizes are very fine to fine sand, and the grains are well- to poorly-sorted and sub-angular to well-rounded. Mostly homogeneous deposits, in places they show heterolithic lithology in discontinuous coarser-grained darker-color lamina. Locally, these deposits display evidence of bioturbation, including *Cruziana*, *Skolithos* (Figure 4.27) and other trace fossils, in addition to evidence of desiccation and syneresis mud cracks in places (Figure 4.28 and Figure 4.29). In the Middle Siq Sandstone in the Al Ula area, this facies occurs as a thickly-bedded unit within which (Figure 4.30). Examples of these flat-laminated sandstones are observed to show double mud drapes (Figure 4.31). These deposits are also found deformed in places.

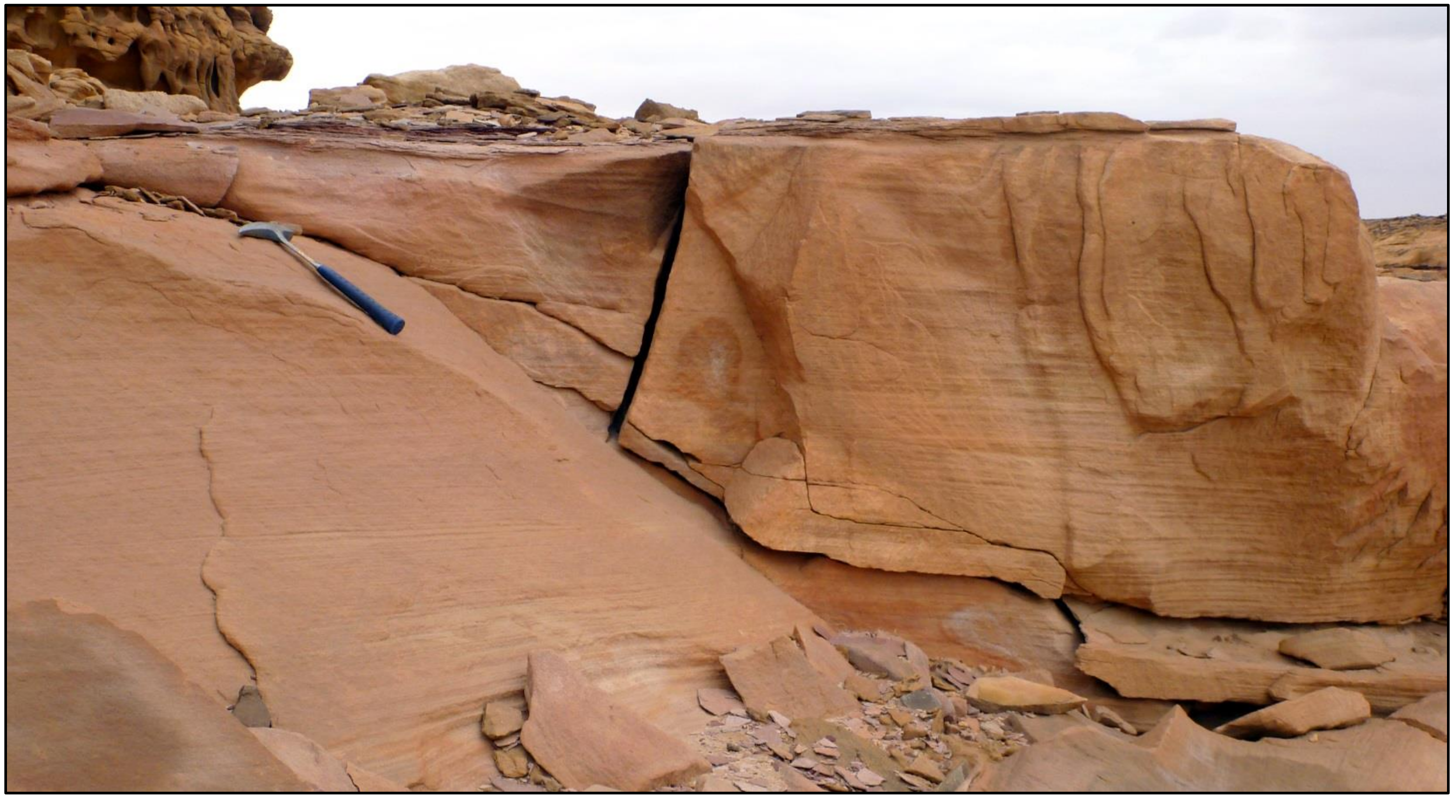


Figure 4.26: Flat-laminated sandstone beds are rarely preserved in studied succession. This particular bed is scoured by succeeding trough cross-bedded sandstone bed on the other side of the outcrop (the Quweira Sandstone in the Al Ula area in section U401 at 3.0 m – Appendix A).

Figure 4.27: Flat-laminated to massive sandstone bed, displaying vertical *Skolithos* trace fossils (measured section T101 at ~15.0 m – Appendix A)

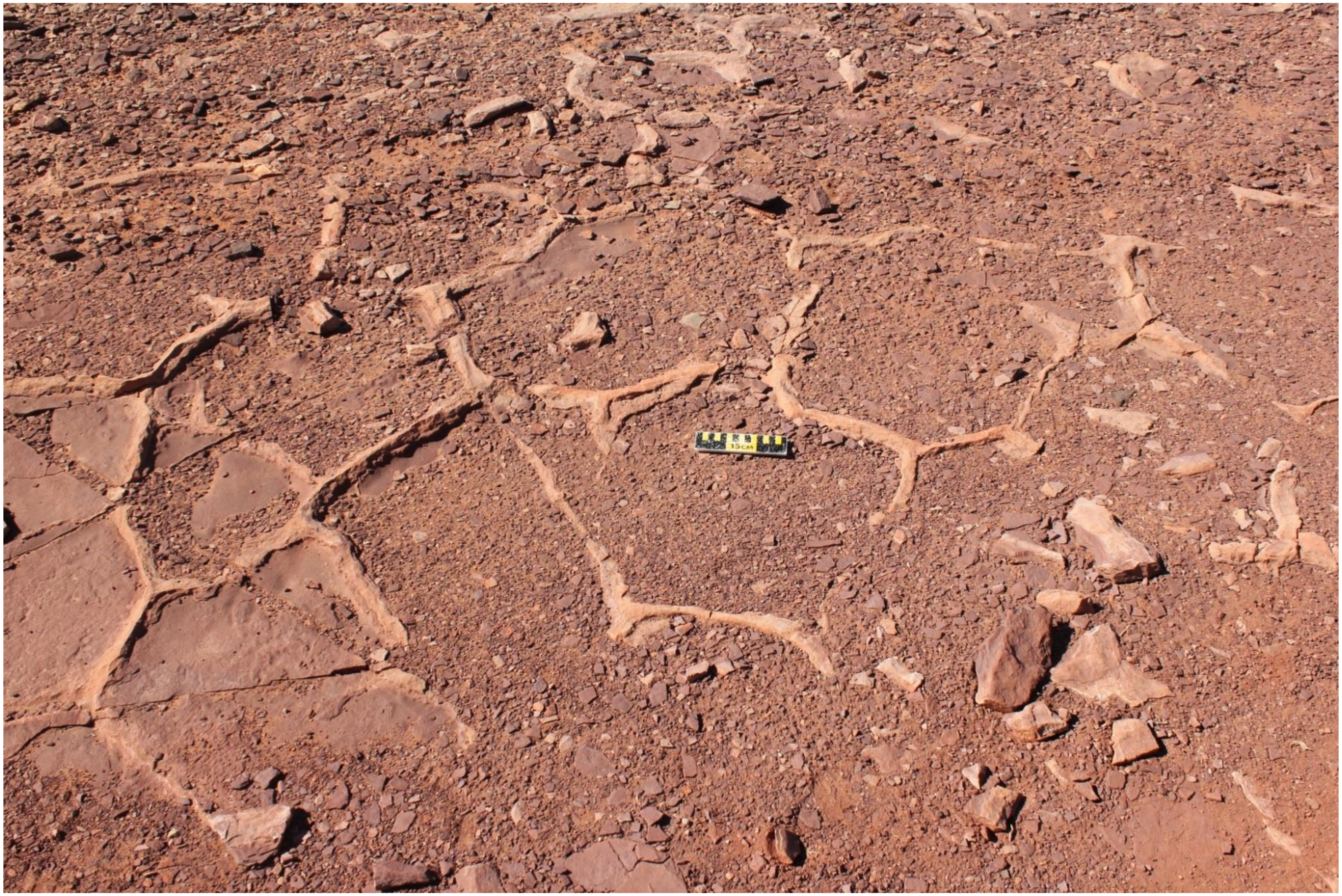


Figure 4.28: A desiccation surface with mud cracks (scale is 15 cm) commonly marks the top of the Upper Siq Sandstone in the Tabuk area – Ash' Shiq area.

Figure 4.29: Massive sandstone beds that shows possible syneresis cracks, recognized by their discontinuous geometries and indicative of water input of fluctuating salinities (top of the Upper Siq Sandstone, immediately below the base of the Quweira Sandstone in the Tabuk area; measured section T101 near Ash' Shiq at 16.0 m – Appendix A).

Figure 4.30: The Middle Siq Sandstone in measured section U101 where the finer-grained Facies 10 succession is easily eroded and covered by scree. Cliff-forming notes the Upper Siq Sandstone at the skyline (see comment in measured section U101, page 5/5; picture taken at 48.0 m – Appendix A).

Figure 4.31: Flat-laminated sandstone bed showing abundance of double-clay drapes and overlying cross-bedded sandstone (the Middle Siq Sandstone in measured section U101 at ~ 41.0 m – Appendix A).

Interpretation:

These deposits (low angle to flat-laminated beds) are mainly found near the top of sequences of channel bar deposits during slack-water phase – Unit C in Coleman (1969). Mostly finer-grained sandstones and silty to argillaceous deposits with local presence of bioturbation, similar sequences in the Brahmaputra and Saskatchewan Rivers are found on the tops of sand bars, indicating waning flow, possibly as a result of channel migration and local abandonment (Smith, N. D., 1974; Cant & Walker, 1978). The observation of double-clay drapes is a strong indicator of a tidal depositional setting and variations in tidal current velocities (Dalrymple, 1992). Trace fossils including *Skolithos* and *Cruziana* are indicative of variable upper shoreface to lower offshore depositional setting (Pemberton et al., 1992), or possibly a drowned estuarine-river valley due to transgression (Weil, 1977). Different shrinkage cracks observed in this facies are either the result of desiccation due to possible subareal exposure of abandoned channel bars or intertidal zones (Reineck & Singh, 1973), or as a result of syneresis due to fluctuations in water salinity (Burst, 1965) in an estuarine setting. Deformation observed is possibly the result of non-uniform confining pressures of overlying bedding (Allen, 1982; Mills, 1983) – see Facies 11, 12 and 13; which is thought to have resulted in reworking laminated beds into massive sandstone beds of this facies.

Facies 11. Deformed Sandstone:

Description:

Facies 11 is commonly observed throughout the succession in both the Al Ula and Tabuk areas and it represents less than 6% of the total measured footage. It includes beds that were originally deposited as any of the other facies listed previously, and then were altered due to soft sediment deformation. This includes features such as oversteepened foresets (Figure 4.32) and fluid/sediment redistribution (Figure 4.33). Grains vary in sizes, shapes and sorting, and beds vary in thicknesses with respect to their stratigraphic position. These beds are either found isolated as a single deformed set or as multiple deformed beds (see Facies Association 6).

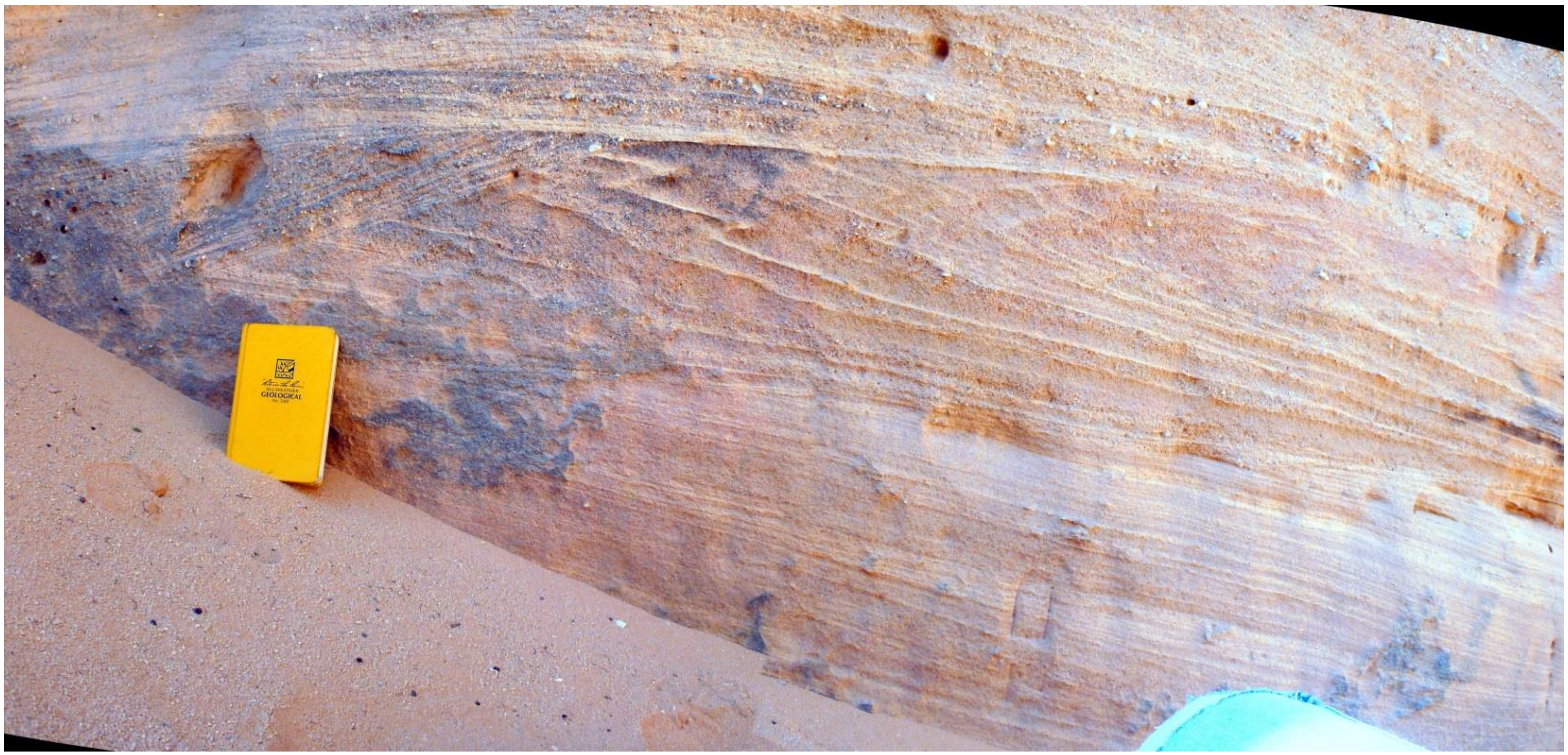


Figure 4.32: Oversteepened and recumbent-folded foresets in a trough cross-bedded sandstone bed as a result of rapid sedimentation (the Quweira Sandstone in measured section U202 at Ad’ Diwan section in Mada’in Saleh at 3.5 m – Appendix A).

Figure 4.33: Deformation in conglomeratic trough cross-bedded sandstone set resulting in a fluid/sediment redistribution, probably due to fluidization and destruction of cross-bedding (measured section U202a at Ad' Diwan section in Mada'in Saleh at 4.0 m – Appendix A).

<u>Interpretation</u>:

Facies 11 deformed deposits are the result of different deformation mechanisms. Suggested mechanisms to have caused deformation of sandstone beds in this study include non-uniform pressure from overlying beds, fluid flow at the fluid-sediment interface, fluid flow within sediments (Allen, 1982; Mills, 1983), rapid sediment loading, and possibly slumping (Moretti & Sabato, 2007; Owen & Moretti, 2008). Processes such as rapid sedimentation, liquefaction (Reineck & Singh, 1973) and dewatering (Bristow, 1993b) are believed to be the driving force behind the deformation of these sandstones. Moreover, seismic activity has been discussed as a common cause of such deformations in areas where tectonic instability can be illustrated (Allen & Banks, 1972; Owen & Moretti, 2008). More recent studies illustrating the different types of deformed facies in fluvial/tidal interaction setting are included in Pisarska-jamroży and Weckwerth (2013).

Facies 12. Cross-Bedded Sandstone with Overturned Foresets

<u>Description</u>:

This special facies emphasizes the presence of cross-bedded sets with overturned, recumbent-folded foresets. Found at around 3.0% of total measured footage, these sets are found throughout the succession in both the Al Ula and Tabuk areas. Mostly occurring as isolated cross-bedded sets with overturned foresets, they are also found in groups of multiple cross-bedded sets with overturned foresets (see Facies Association 6). Internal overturned-foresets are observed at variable angles of folding in sets of variable thickness and in different facies (Figure 4.34).

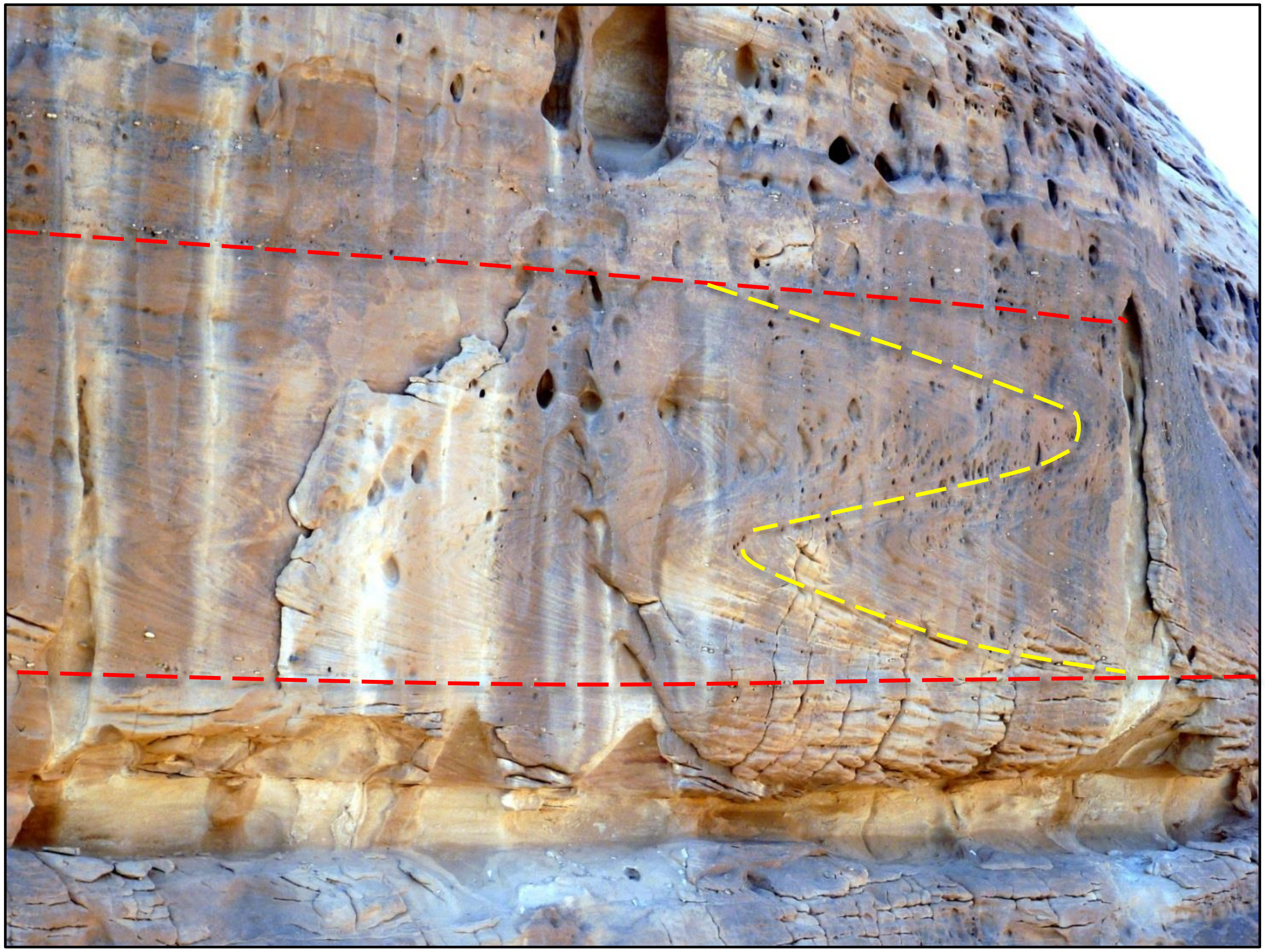


Figure 4.34: Cross-bedded sandstone beds showing folded foresets (middle to higher in the Quweira Sandstone in measured section U202a at Ad' Diwan section in Mada'in Saleh at 21.5 m – Appendix A).

<u>Interpretation</u>:

Sandstones in this facies are indicative of soft sediment deformation as a result of different deformation mechanisms, discussed in Facies 11. Possibly due to dewatering and rapid sedimentation (Reineck & Singh, 1973), it has also been argued that tectonic activity may result in shear force through complete liquefaction and fluidization of beds, which allows the overturning of foresets in these cross-bedded beds (Allen & Banks, 1972; Owen & Moretti, 2008).

Facies 13. Intensely-Deformed Sandstone

<u>Description</u>:

Sandstone beds of this facies are intensely-deformed to the point that primary bedding is nearly-completely destroyed and laminations cannot be observed. Occupying less than 2.0% of total measured footage, it is limited to the Lower Siq and the middle part of the Quweira, in addition to the Saq Sandstones in the Al Ula area. It is limited to parts of the Quweira and the Saq Sandstones in the Tabuk area. This facies generally displays a poorly-sorted fabric. It is commonly associated with Facies 14, and it also includes beds that show convoluted beds and dm-scale fluid-escape structures (Figure 4.35 and Figure 4.36).

Figure 4.35: Intensely-deformed sandstone bedding (below Facies 14 deposits) within the Quweira Sandstone, which shows complete deformation due to convolution and fluidization (measured section T103b in the Tabuk area at ~ 6.0 m – Appendix A).

Figure 4.36: Deformed sandstone bed that displays a fluid-escape structure (measured section T102 at ~13.5 m – Appendix A).

<u>Interpretation</u>:

Intense deformation is a reflection of excessive fluidization of these units in the succession. Including convolution and fluid-escape structures, such features are indicative of significant dewatering, possibly as a result of non-confined pressure of overlying beds or seismic activity (Allen, 1982; Mills, 1983; Bristow, 1993b). Convolution is possibly indicative of shear stress caused by sudden rise in turbulence, which initiates liquefaction of underlying beds (Coleman, 1969). Such deformed facies are commonly observed and recorded in the lower part of fluvial channel bar deposits (Reineck & Singh, 1973).

Facies 14. Very Poorly-Sorted Paraconglomerate

<u>Description</u>:

This facies occurs in only one place in this study, namely in the middle of the Quweira Sandstone in the Tabuk area (measured section T103b at 4.0-12.5 m – Appendix A). Three beds display a range of very poorly-sorted pebble- to cobble-sized clasts supported in a matrix of medium- to coarse- sand grains in a very poorly-sorted and sub-angular to sub-rounded sandstone. These beds show poorly developed coarse-tail grading (Figure 4.37) and dispersed pebble-size quartz, subordinate feldspars and granitic clasts of different sizes and shapes (Figure 4.38). This bedding appears to be overlying deformed sandstone beds of Facies 11 and 13.

Figure 4.37: Very poorly-sorted paraconglomerate bed showing grading (measured section T103b at 7.0 m - Appendix A).

Figure 4.38: Base of paraconglomerate (measured section T103b at ~ 4.0 m – Appendix A) showing concentration of various quartz and igneous clasts, including circled example showing a ~ 15 cm cobble of granite.

<u>Interpretation</u>:

Facies 14 deposits are interpreted to be the product of debris flow deposition (Stanley, 1969), characterized by extremely poor-sorting and poor-grading pebbly fabric. The debris flow is believed to have been initiated by a catastrophic event (Heezen & Drake, 1964). Observing the variable pebble types, sediments may have transported for a distance as a gravity flow. Catastrophic events can result from different processes, such as seismic activity or severe climatic conditions. Deformation of underlain bedding is probably caused by non-confined pressure of overlying (Facies 14) debris flow, or as a result of the same catastrophic event.

4.1.2 Facies Associations

Following the description of all depositional facies in the previous section, facies are grouped into recognized facies associations. Seven facies associations (FA) are identified in this study between both study areas near Al Ula and Tabuk, and they represent variable depositional settings. Changes in facies associations imply changes in depositional setting within or between the different sandstone units in the succession, as well as paleogeographic variations between the Al Ula and Tabuk study areas. Facies associations are listed based on similarities in sedimentary processes, depositional settings, and extrabasinal sources. Figure 4.39 and Figure 4.40 display selected examples of the different facies associations recognized in this study, in both the Al Ula and Tabuk areas.

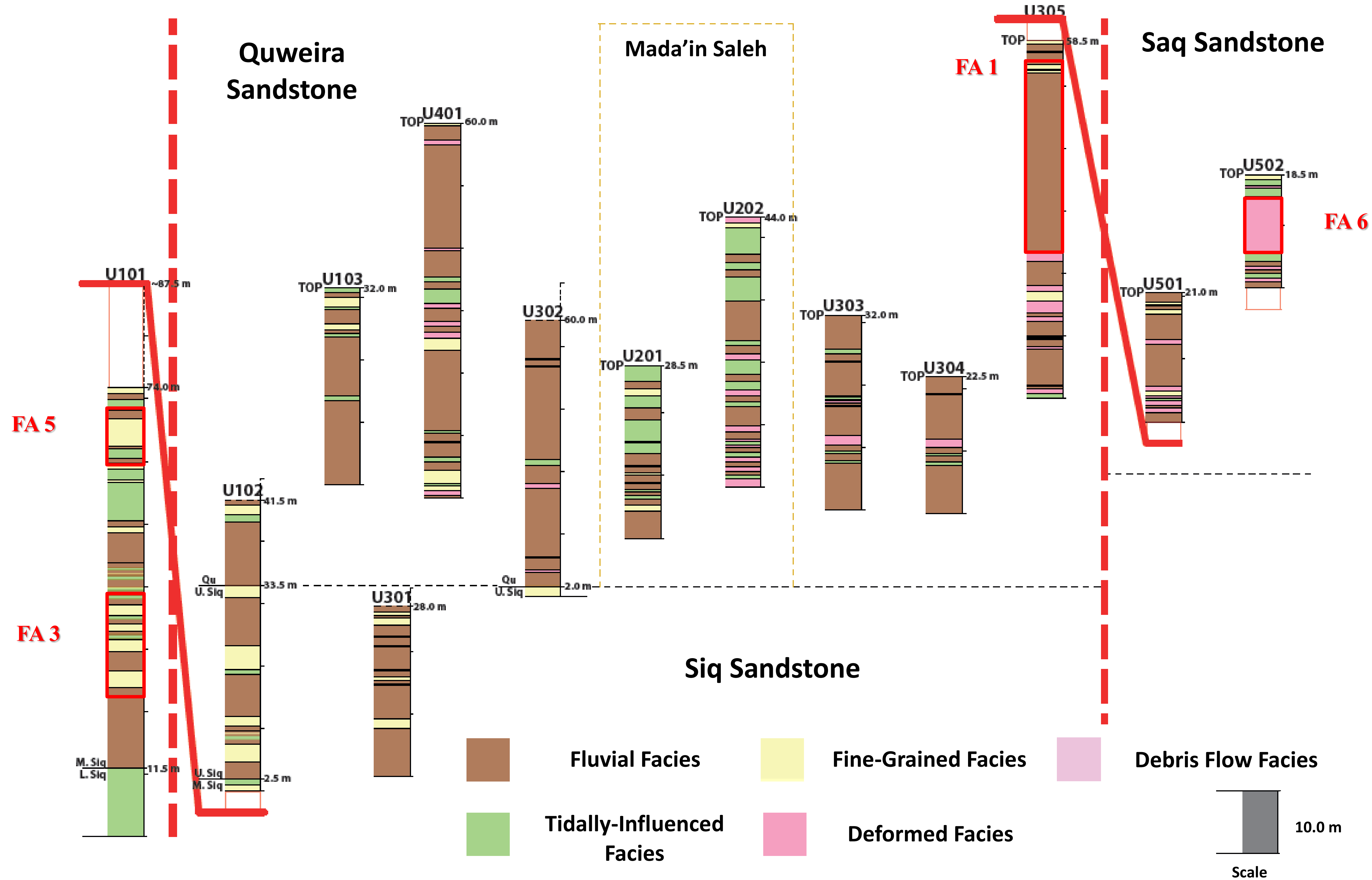


Figure 4.39: Correlation of measured sections in the Al Ula area, highlighting selected examples of the different facies associations in this study

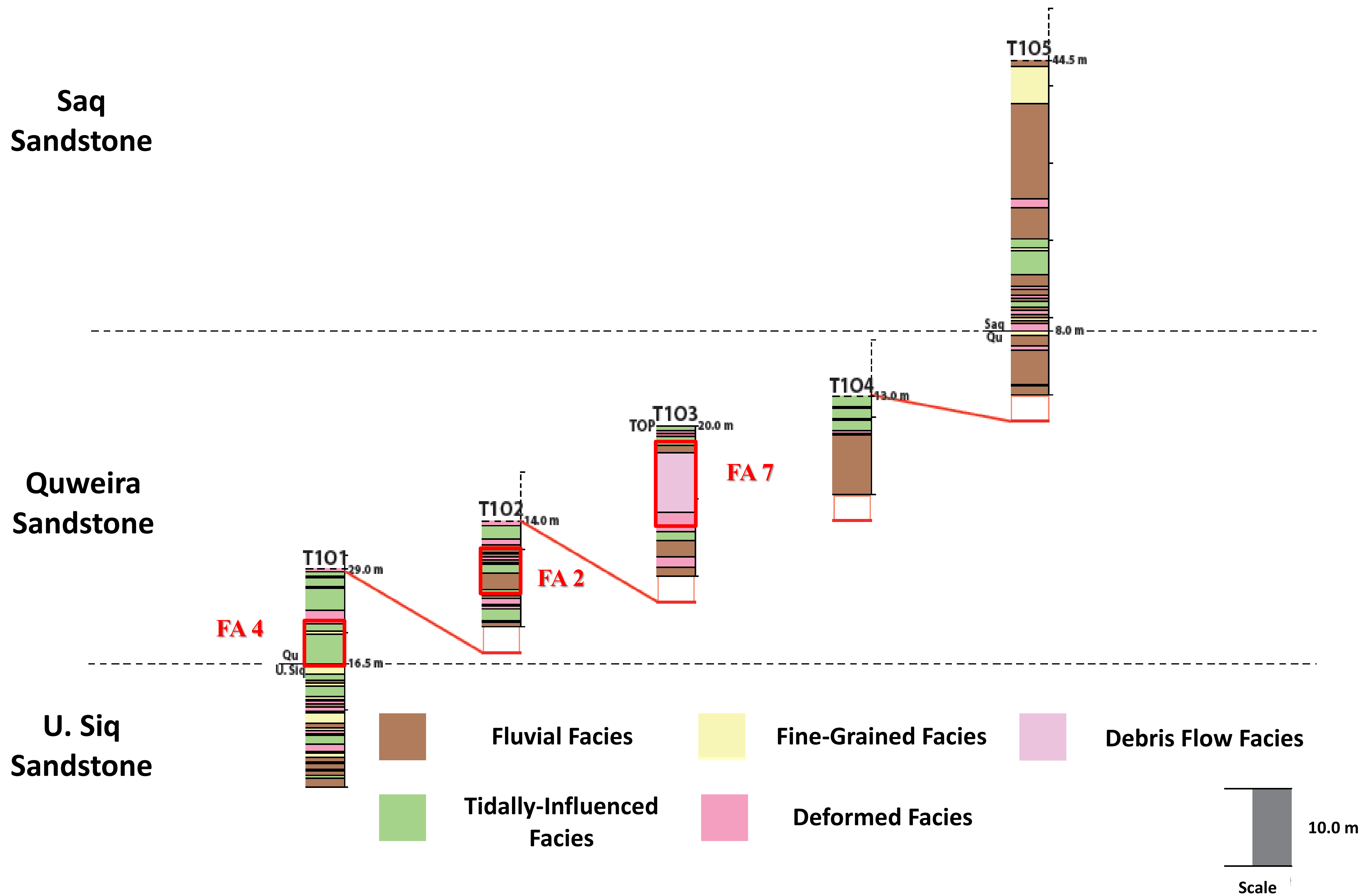


Figure 4.40: Correlation of measured sections in the Tabuk study area, highlighting selected examples of the different facies associations in this study

Facies Association 1. Fluvial-Dominated I

This facies association is characterized by braided-fluvial channel deposition in fining-upward sequences (Figure 4.41). Including conglomerates and sandstones of Facies 1 through 5, this facies association, in its lower parts, represents high-energy deposition of in-channel and sand flat braided-fluvial sandstone facies. Locally, these sequences are topped by fine-grained sandstones of Facies 9 and 10. Indicating waning flow in these fluvial successions which is probably related to channel migration in a braided fluvial depositional environment, these finer-grained tops are commonly scoured into by overlying in-channel bar deposits as a result of recurring bar migrations.

Facies Association 2. Fluvial-Dominated II

This facies association displays braided-fluvial channel deposits at bases and show increased tidal influence higher in fining-upward sequences (Figure 4.42). Fluvial facies include Facies 1 through 5, and show development of facies 6 through 8 above. Similar to FA1, sequences are locally topped by fine-grained sandstones (Facies 9 and 10), that are commonly scoured away due to subsequent channel migration, or variable tidal currents in this facies association. In addition of showing tidally-influenced sandstone facies, these beddings also show evidence of bioturbation in places. These sequences represent braided-fluvial sedimentation that is subject to marine flooding, possibly in an estuarine setting.

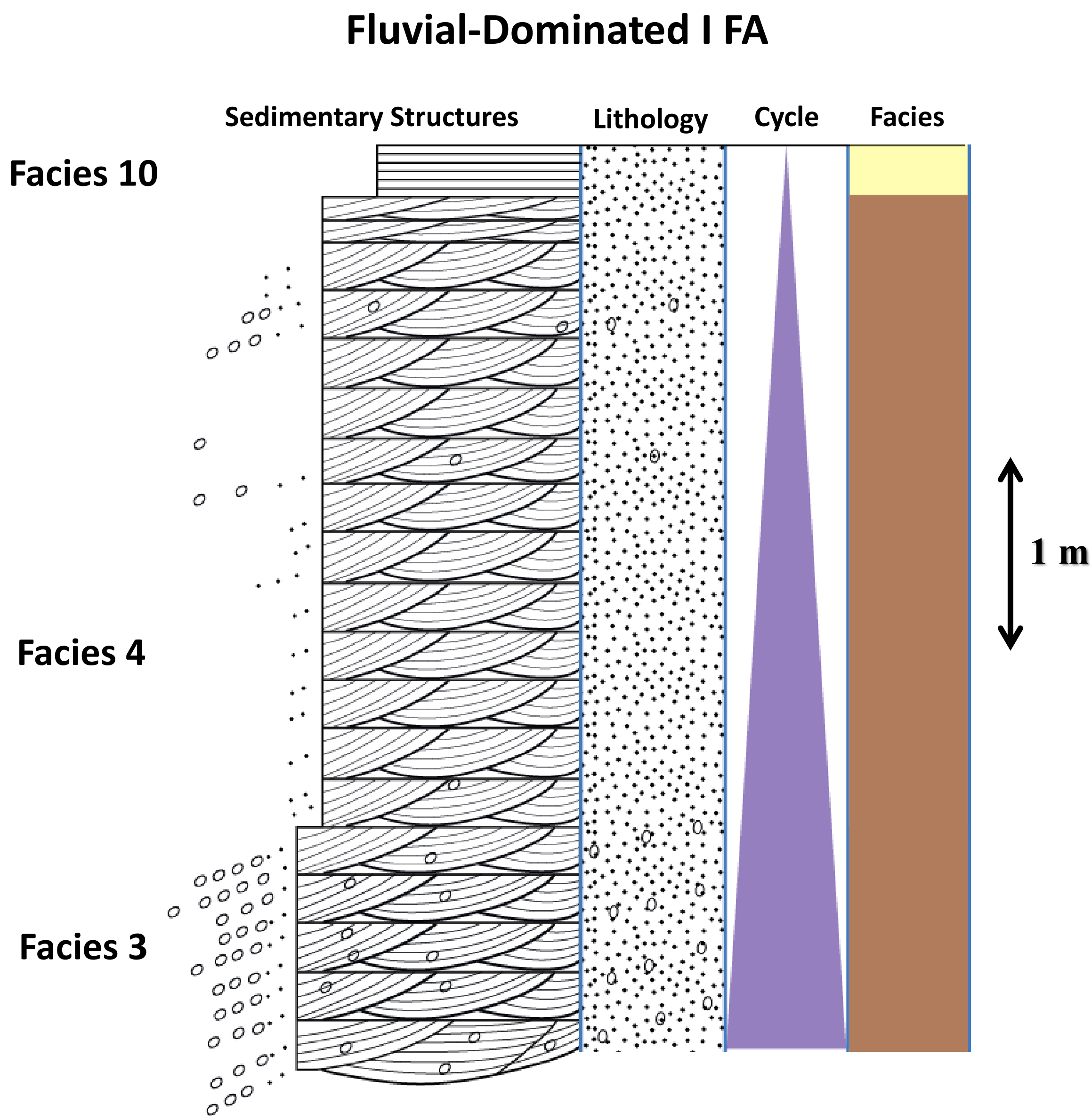


Figure 4.41: Example of fluvial-dominated I facies association, characterized by fining-upward braided fluvial channel deposits, topped by fine-grained sandstone facies (measured section U305 between 48.5 and 53.5 m – Appendix A).

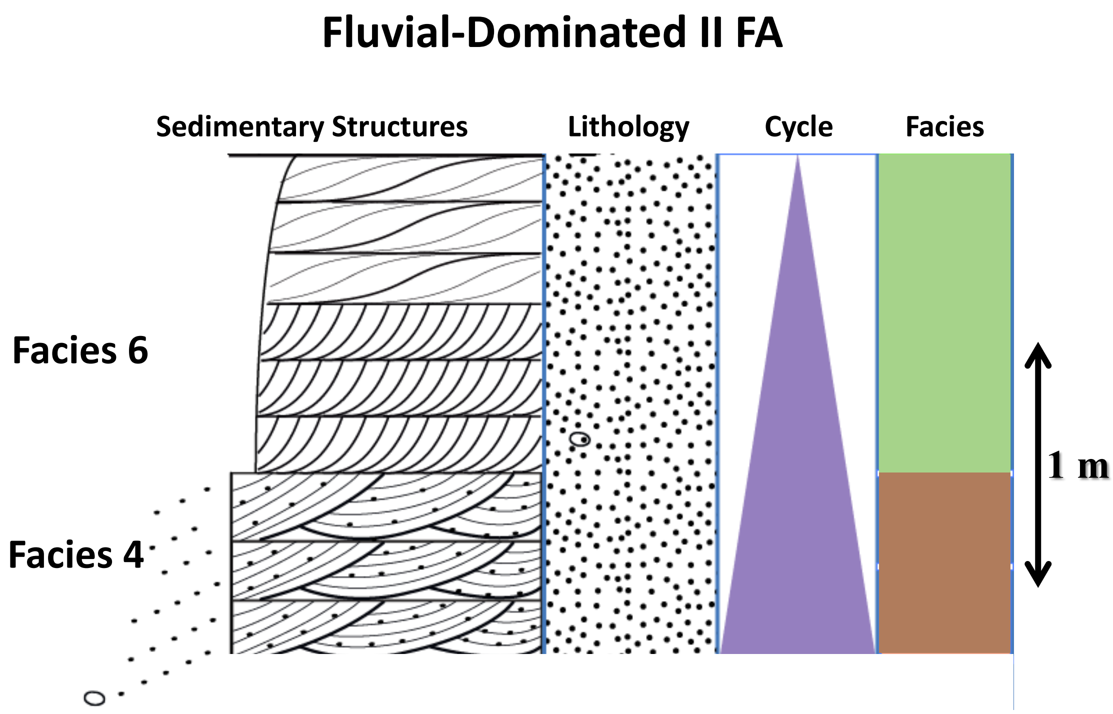


Figure 4.42: Example of fluvial-dominated II facies association, characterized by fining-upward braided fluvial channel deposits that change into tidally-influenced facies higher in the sequence (measured section T102 at 6.5 – 8.5 m).

Facies Association 3. Mixed Fluvial-Tidal (Estuarine) Association

These sequences include relatively thinly-interbedded braided-fluvial facies (1-5), high-energy tidally-influenced facies (6-8) and low-energy fine-grained facies (9-10) that suggest both fluvial and tidal influence in fining-upward sequences (Figure 4.43). With an overall sand-rich distribution and thinner beds and sequences, this facies association is interpreted to have been deposited within an estuarine setting. Common scouring of tops of cycles leads to the abundance of intra-formational mud clasts observed in these strata. This facies association is predominant in the Middle Siq Sandstone unit in the Al Ula area measured sections (namely U101 – Appendix A).

Facies Association 4. High-Energy Tidally-Dominated

This facies association is characterized by fining-upward sandstone sequences that show predominant tidal influence (Figure 4.44). Facies 6 through 8 sandstone deposits show different characters of tidal-influence. Bases of sequences locally show coarser-grained (massive) sandstone beds, interpreted as base tidal-channel deposits. Tops of cycles are locally topped by lower-energy finer-grained, argillaceous bedding (Facies 9 and 10), interpreted as mud flats. This facies association is found variable in distribution, in addition to degree of tidal-influence. These are possibly dependent on the location within the estuary during deposition.

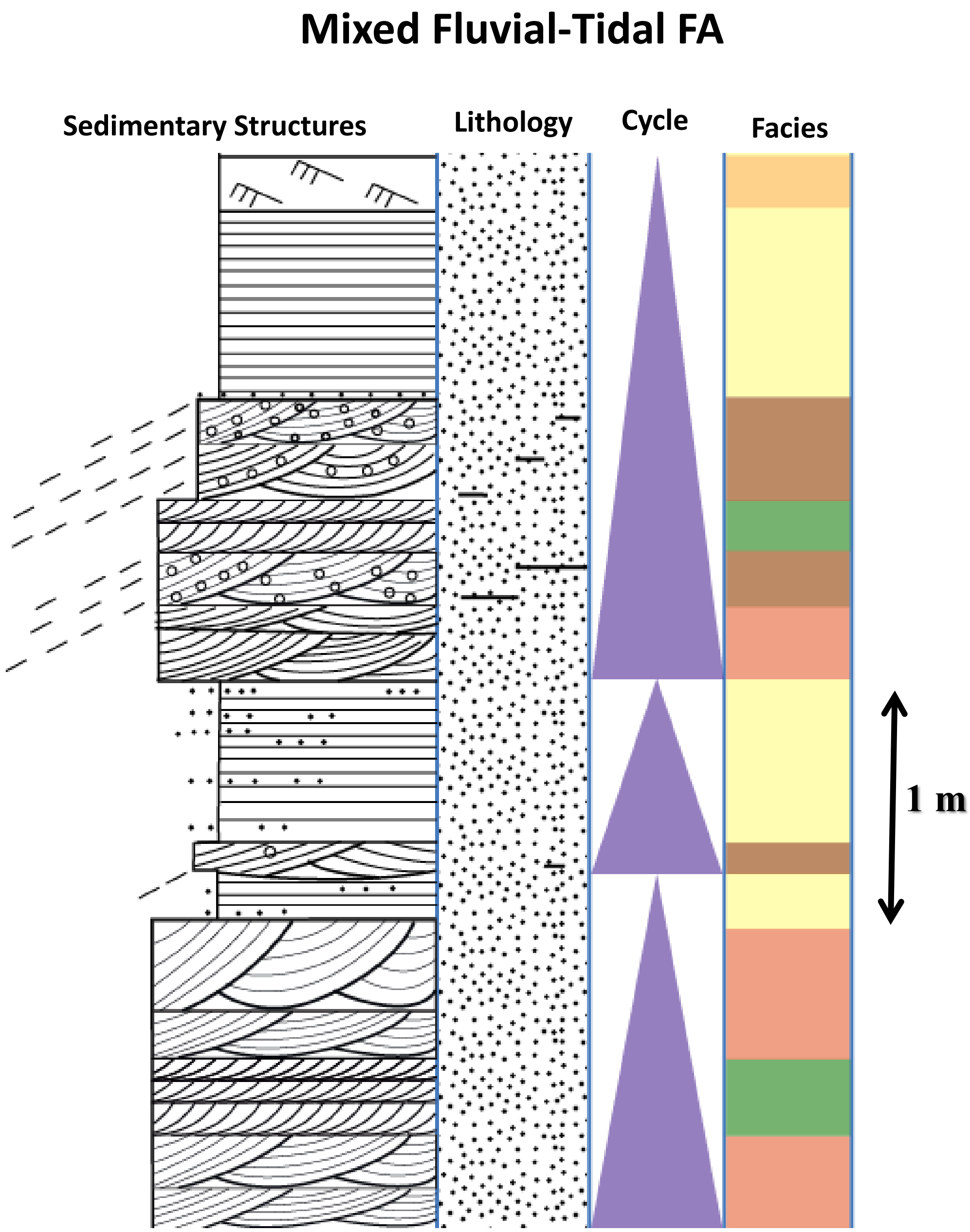


Figure 4.43: Example of fluvial-tidal mixed facies association, characterized by fining-upward mixed facies deposits that include braided fluvial channel deposits, interbedded with both high-energy and low-energy tidally-influenced deposits (measured section U101 between 32.5 and 37.5 m – Appendix A).

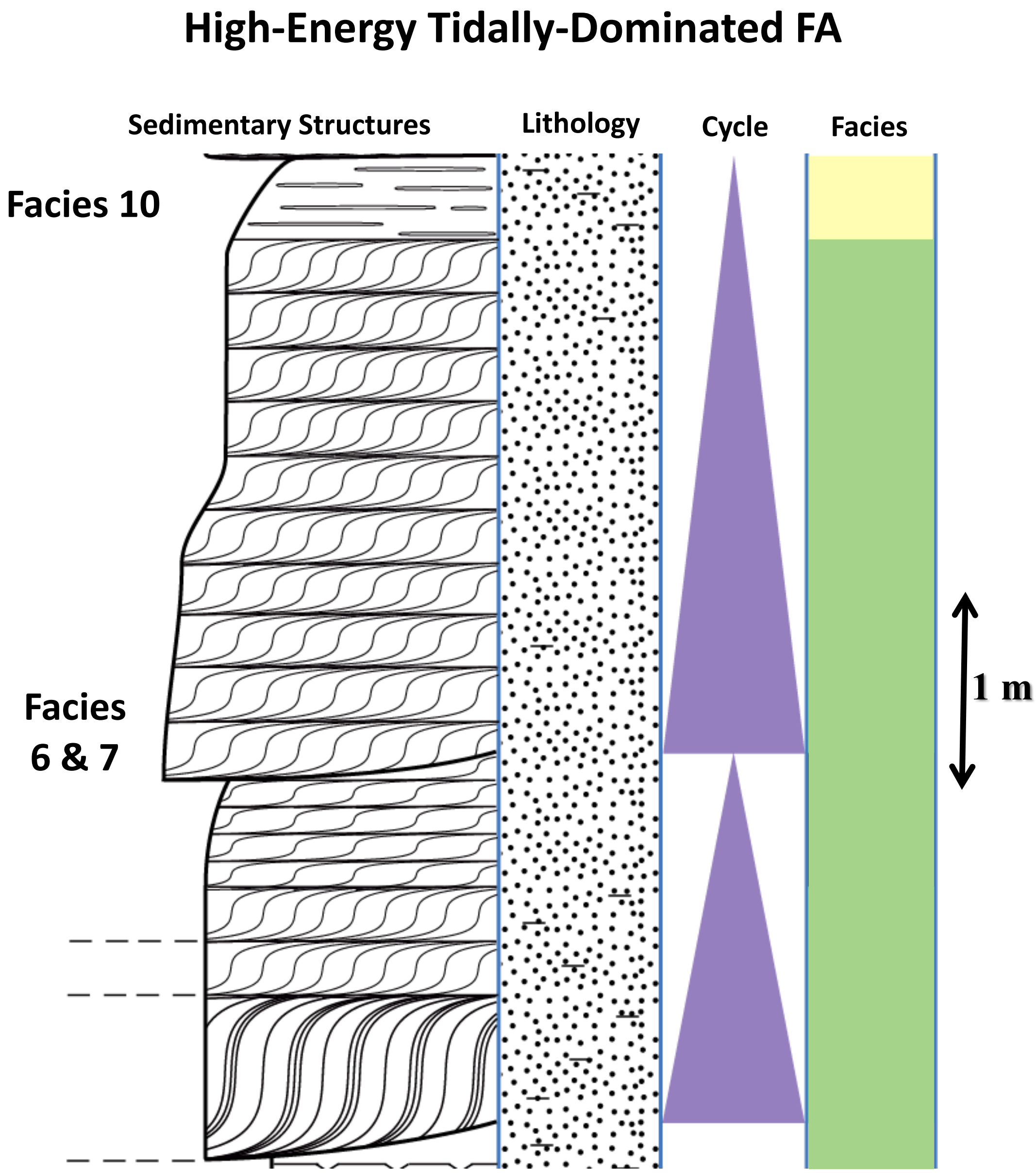


Figure 4.44: Example of high-energy tidally-dominated deposition of tidal sand flats in this study. Fining-upward cycles are indicative of possible deposition within an estuary (measured section T101 between 16.5 and 20.5 m – Appendix A).

Facies Association 5. Low-Energy Tidally-Dominated

Sandstone beds in this facies association are dominated by fine-grained deposits (Facies 9 and 10), which show tidal signature in places. Sequences show coarser-grained braided fluvial sandstones at the base (Facies 3 and 4), fining-upward into the fine-grained deposits (Figure 4.45). This facies association principally displays examples of lower-energy, fluvial channel waning and possibly sediment starvation periods, where sediments are continuously reworked in a tidal setting. It is limited in studied succession in both study areas (the Middle Siq Sandstone in measured section U101 – Appendix A). As discussed in Facies 9 and 10 descriptions, heterolithic components are possibly obscured due to weathering. Mud content is difficult to quantify in overall relatively-steeper, poorly-exposed outcrops (Figure 4.30). Scouring of tops of cycles is indicated by the increased intra-formational mud clasts concentrated in lower beds of these sequences, and suggestive of channel bar migrations in a distal fluvial, tidally-influenced setting.

Facies Association 6. Deformed Sandstone

Isolated deformed sandstone beds are locally found associated in complete sequences (Figure 4.46). Pervasive deformation of individual beds allows this facies association to be observed. Generally including Facies 11 through 13, deformation within these sequences is variable and bed characteristics are dependent on original bedding and depositional setting.

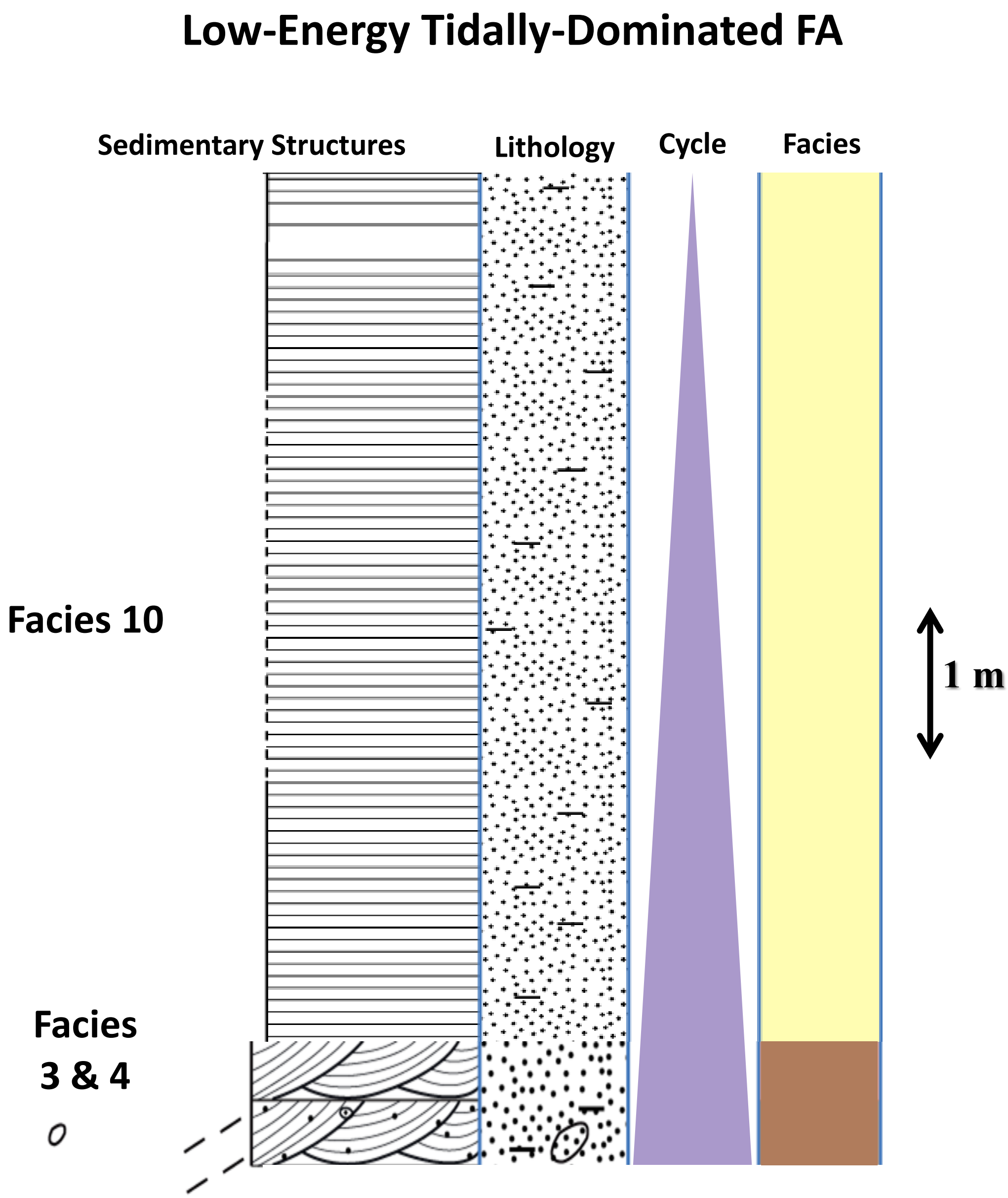


Figure 4.45: Example of low-energy tidally-influenced facies association, illustrating deposition of tidal sand and mud flats in this study. Fining-upward cycles are indicative of possible deposition within an estuary (measured section U101 between 63.5 and 69.0 m – Appendix A).

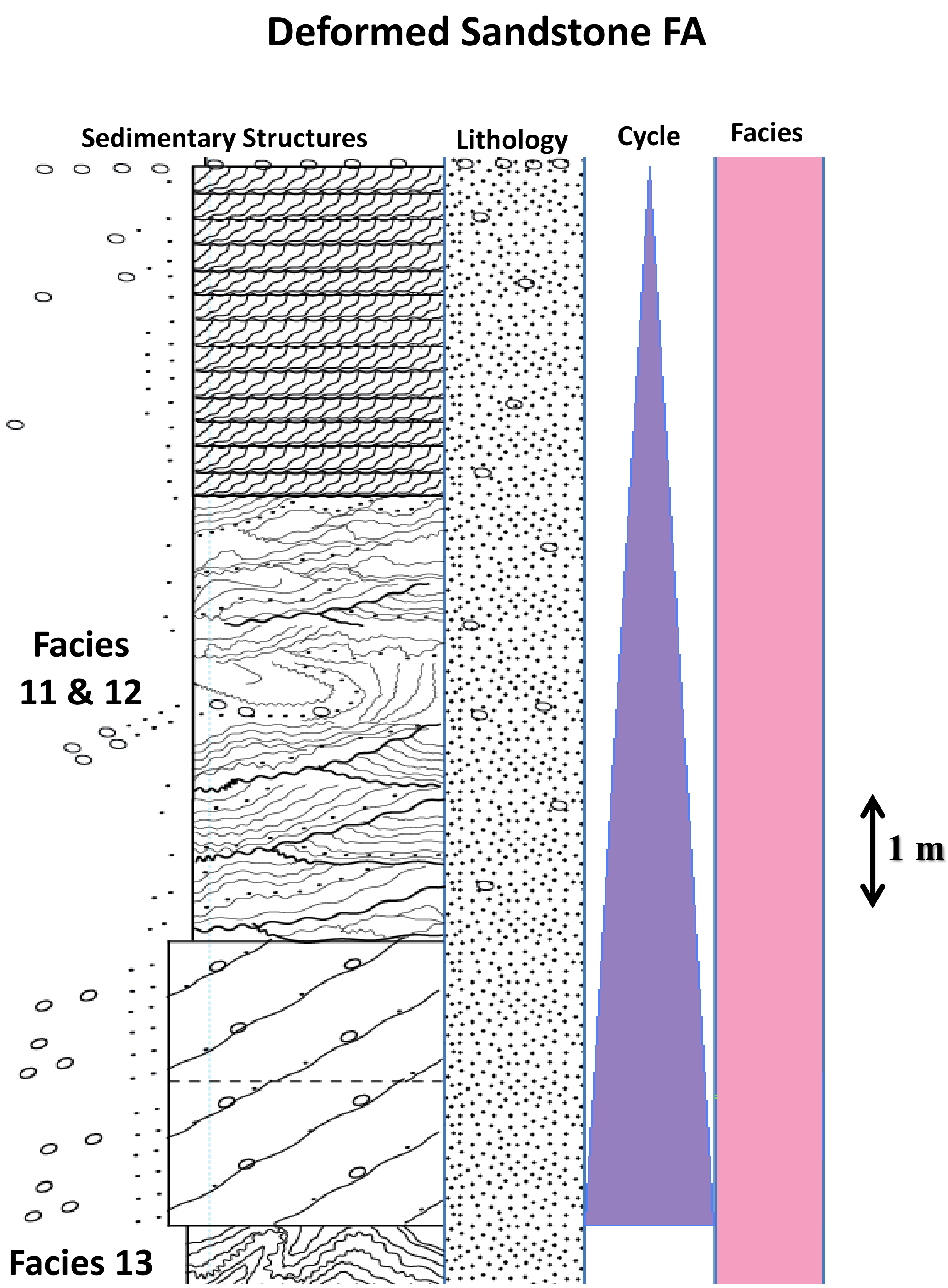


Figure 4.46: Example of deformed sandstone facies association (measured section U502 between 8.0 and 15.0 m – Appendix A).

Facies Association 7. Catastrophic Deposition (?) – Debris Flow

This facies association developed through the local deposition of very poorly-sorted paraconglomerates, interpreted as debris flow deposits in the Tabuk area (see Facies 14). These deposits are found associated with deformed facies underneath (Facies 11 and 13). This facies association possibly resulted from catastrophic deposition in this part of the succession. The deformation of underlying beds is either the result of the impact of rapid sedimentation of paraconglomerate beds or the same catastrophic event described (Figure 4.47).

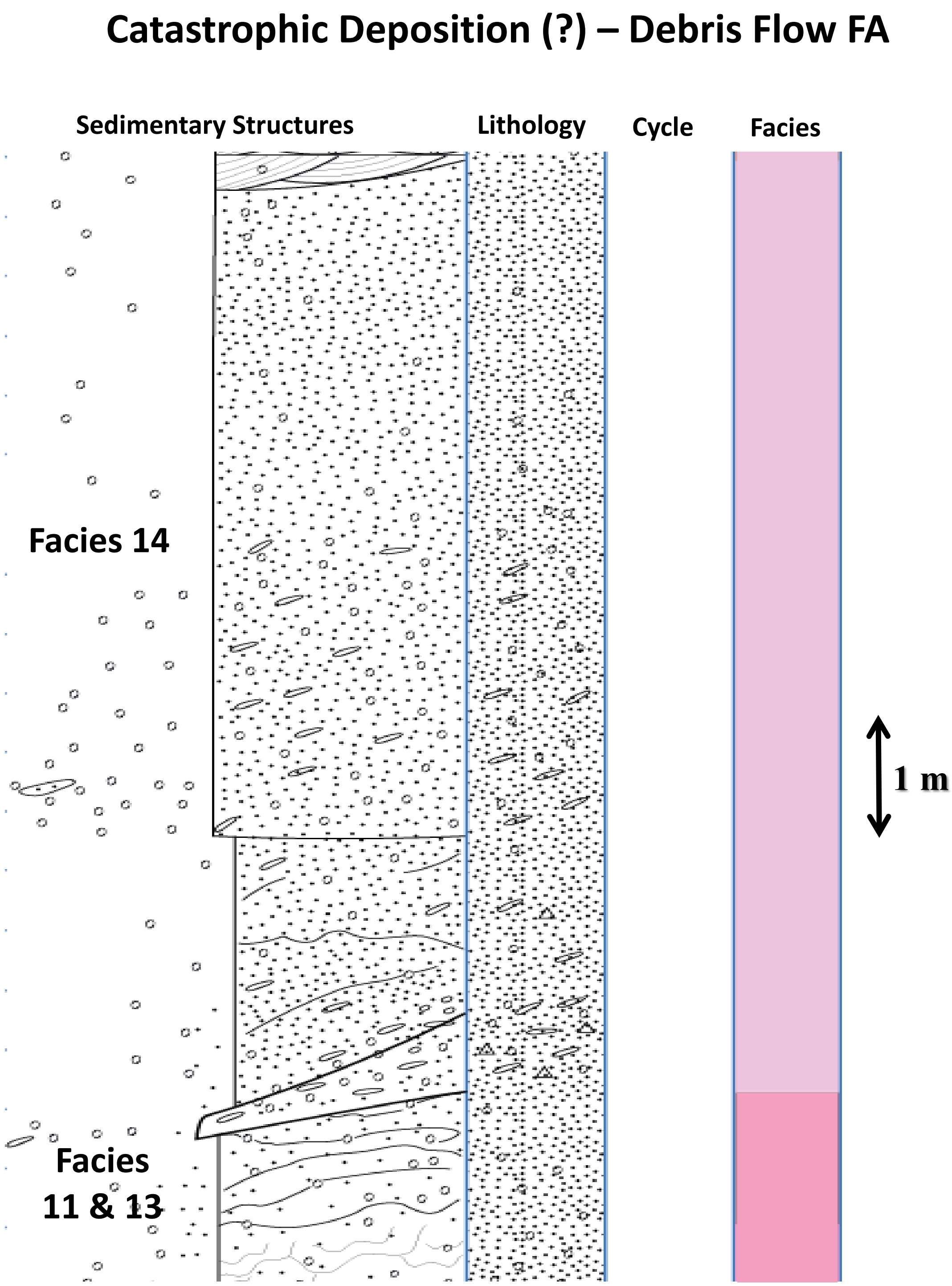


Figure 4.47: The example of catastrophic deposition (?) facies association, found locally in the Tabuk area (measured section T103b between 3.0 and 12.5 m – Appendix A).

4.1.3 Facies Distribution

Thickness measurements of each of the 14 facies described were obtained from all the measured sections and a dataset was created to demonstrate changes and differences in facies distributions throughout the succession and between the two study areas. This demonstration was firstly established by calculating the footage of each facies described with respect to location (the Al Ula verses Tabuk areas), area (line of section), measured section and sandstone unit (Appendix A). Pie charts were then created to illustrate variations of distribution of facies relative to location, area, measured section and sandstone unit. This was done to help identify any lithostratigraphic and possibly paleogeographic variations with respect to described facies in the clastic succession. Facies distribution in the different sandstone units in this section will be described in terms of observed facies associations.

Before discussing facies distribution in each study area in detail, Figure 4.48 shows the overall facies distribution in both study areas (i.e. collectively) as well as the Al Ula and Tabuk areas individually. Fluvial deposits have a strong presence throughout the succession in both study areas. In comparison to each other, the Cambro-Ordovician succession in the Al Ula area displays dominant fluvial facies, whereas in the Tabuk area, the facies show variable distribution, including more tidally-influenced deposits, with greater abundance of fine-grained and deformed deposits (and debris flow paraconglomerates which is only observed in the Quweira Sandstone in this area).

Facies groups are identified to categorize the fluvial facies (1 through 5), the tidal facies (6 through 8), the fine-grained facies (9 and 10), and the deformed facies (11 through 13). These allow simple demonstration of the different facies distributions.

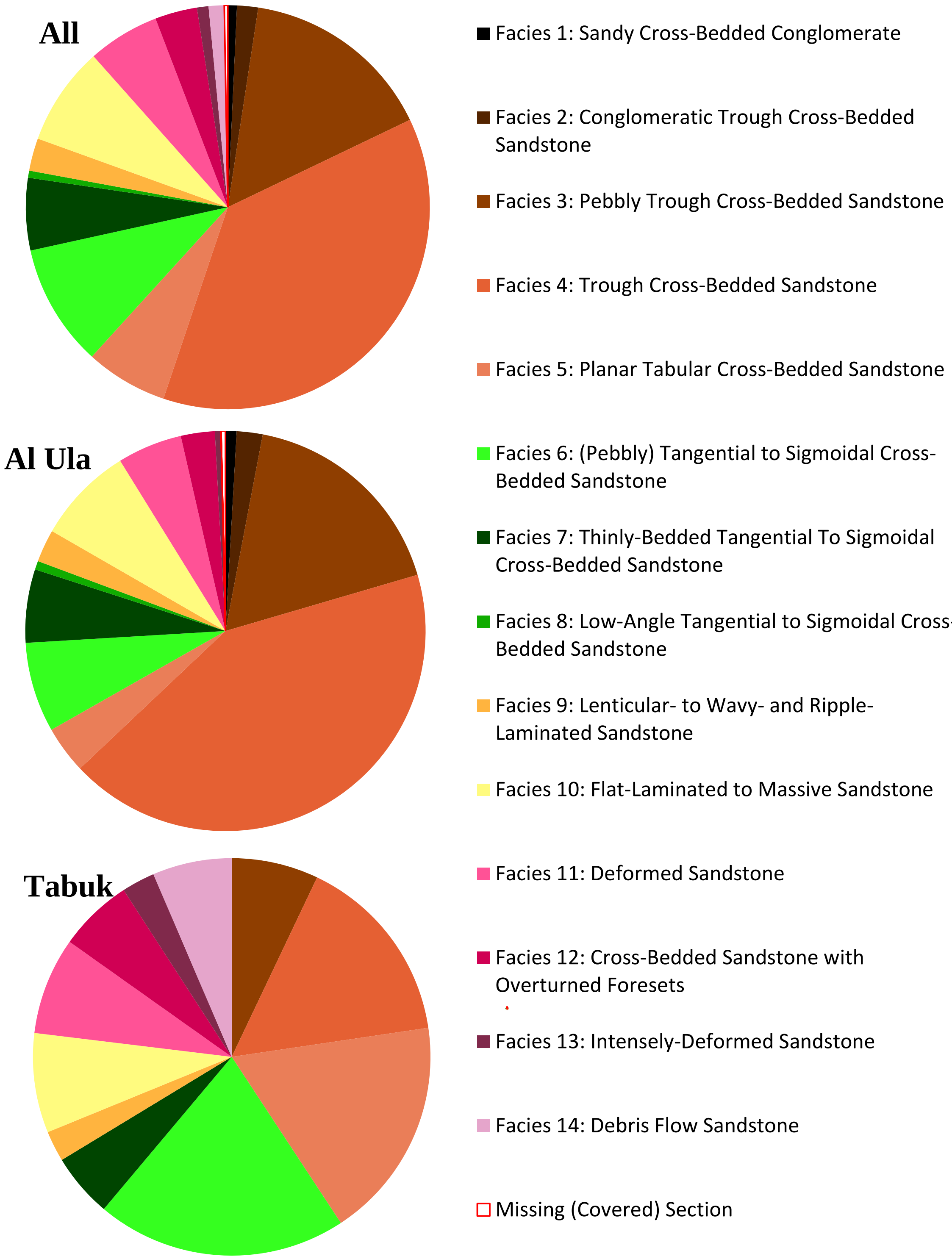


Figure 4.48: Facies distribution within all facies measured in both the Al Ula and Tabuk areas together i.e. throughout the entire study area, and individually as two separate study areas

4.1.3.1 Facies Distribution in the Al Ula Area

The studied part of the Cambro-Ordovician clastic succession in the Al Ula area comprises three sandstone units. These are the Siq, Quweira and Saq Sandstones (Figure 4.49). In gross terms, the Siq Sandstone shows a dominant fluvial facies associations (FA 1 and 2). The remaining is split between mixed fluvial-tidal, high-energy and low-energy tidal-dominated facies associations (FA 3, 4, and 5). FA3 and FA5 are only observed in the Siq Sandstone unit in the Al Ula area. The Quweira Sandstone displays prominent fluvial-dominant facies associations (FA 1 and 2), with variable tidal influence in places (see subsection 2; Facies Distributions in The Quweira Sandstone in the Al Ula area). This is the only sandstone unit that displays Facies 1 and 2 throughout the study in both study areas. Finally, the Saq Sandstone shows a decline in fluvial-dominated facies associations (FA 1 and 2) in comparison with the Quweira Sandstone, and a significant predominance of deformed sandstone facies association (FA 6).

The following sections will demonstrate facies distributions in each of these sandstone units individually.

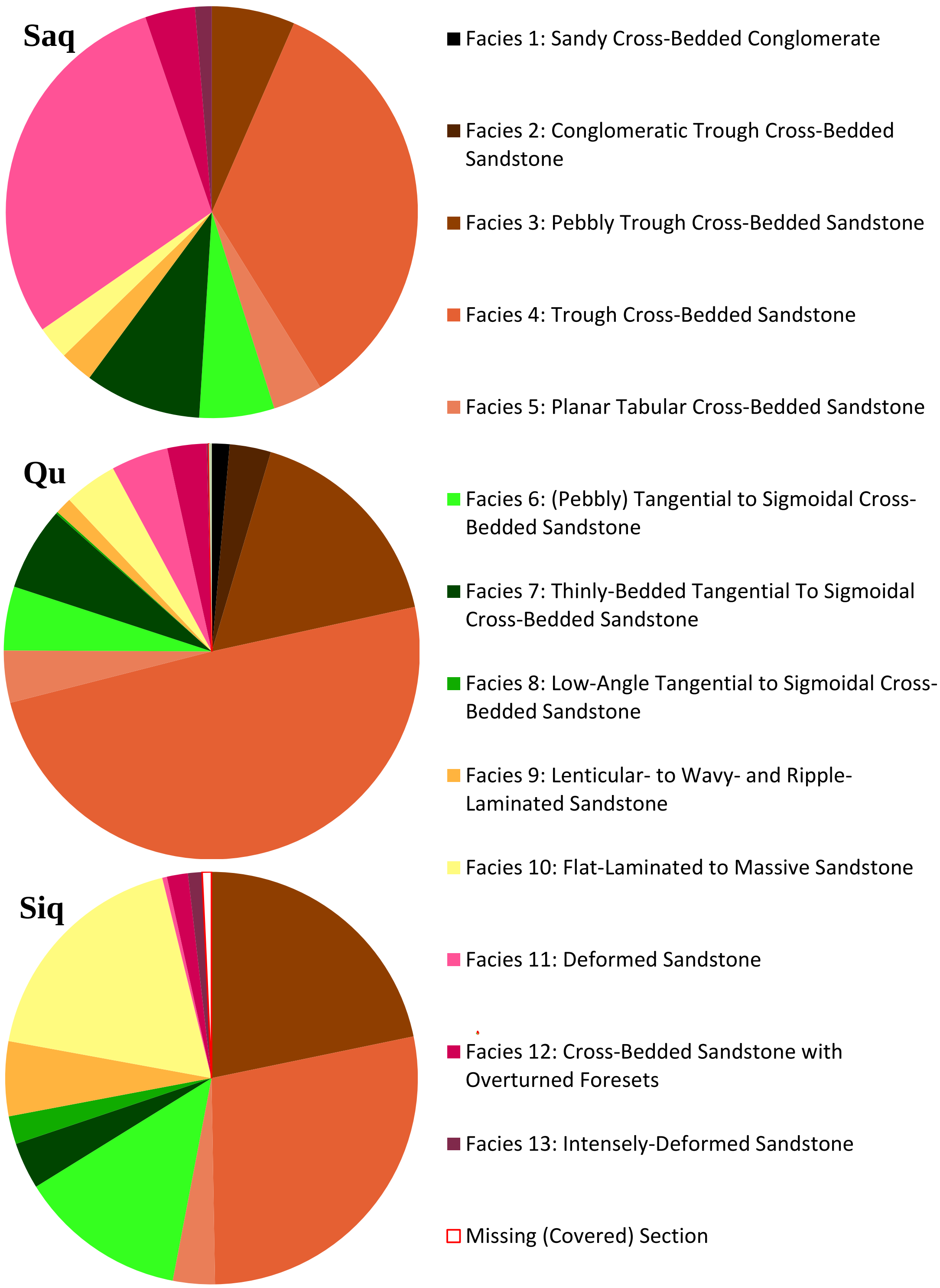


Figure 4.49: Facies distribution within the three sandstone units; the Siq, Quweira and Saq Sandstones in the Al Ula area.

1. Facies Distribution in the Siq Sandstone in the Al Ula Area

The Siq Sandstone is informally divided into the Lower, Middle and Upper Siq Sandstones (see CHAPTER 1, P. 1). Figure 4.50 shows the facies distribution within these three units in the Al Ula area. The facies distribution within the Lower Siq Sandstone is dominated by high-energy tidally-dominated facies association (FA 4) (over 75% of the measured footage; only ~11.5 m in total in this unit due to limited exposure). The remaining footage displays deformed sandstone facies. The Middle Siq Sandstone, on the other hand, shows a fluvial-dominated facies associations (FA 1 and 2; at about 50%) with the remaining footage divided between mixed fluvial-tidal dominated and low-energy tidal-dominated facies associations (FA 3 and 5), where the latter is limited to this sandstone unit in the Al Ula area. The Upper Siq Sandstone shows a dramatically enhanced dominance by fluvial-dominated facies associations (FA 1 and 2). Facies 1, 2 and 14 are not observed in the Siq Sandstone in the Al Ula area.

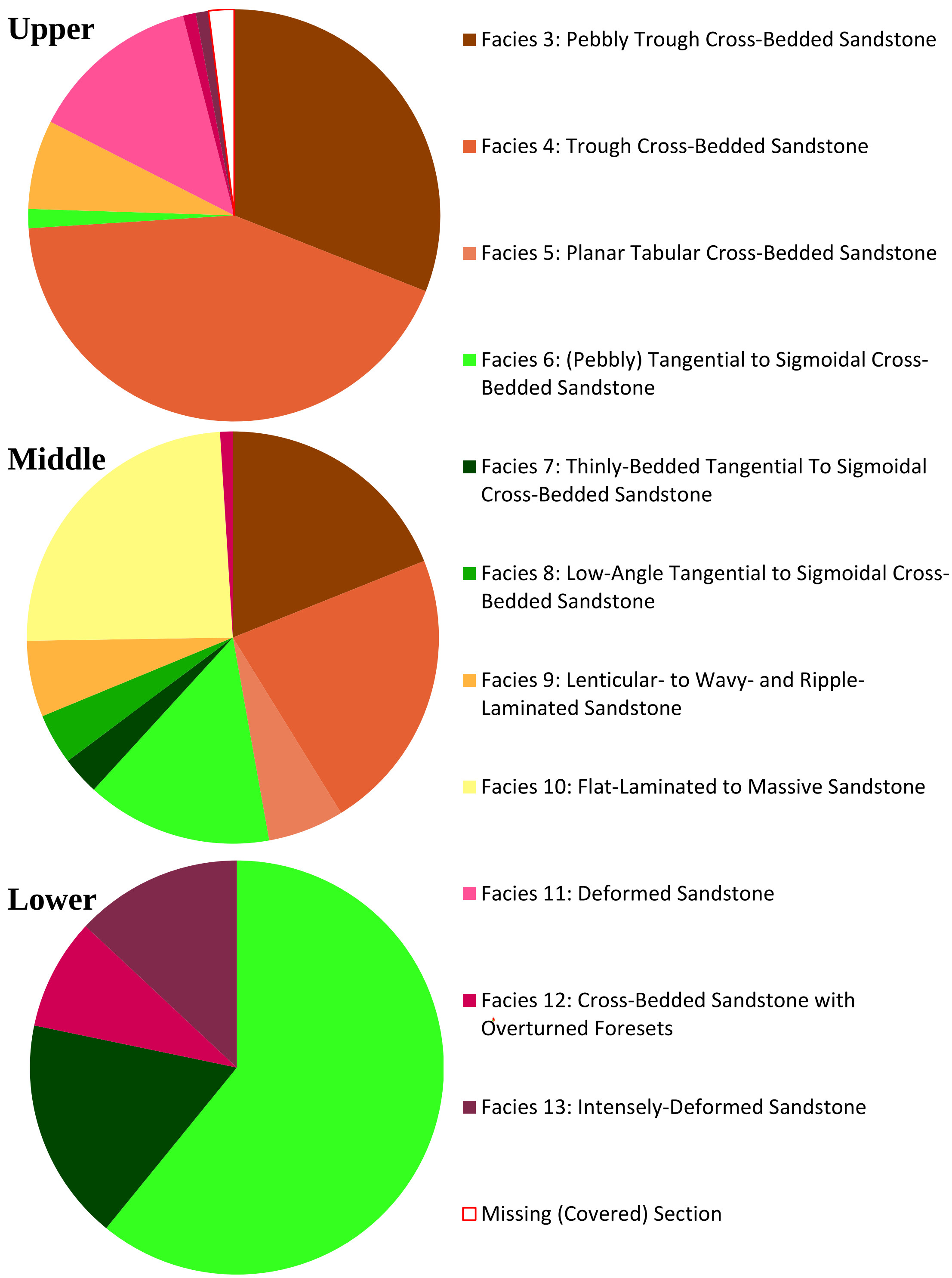


Figure 4.50: Facies distribution within the Lower, Middle and Upper Siq Sandstones in the Al Ula area.

2. Facies Distribution in the Quweira Sandstone in the Al Ula Area

This sandstone unit comprises the majority of studied succession in this study. Due to its high measured footage, the Quweira Sandstone has been informally divided into lower, middle and upper parts in this study. Since no definite boundaries mark these distinctions, estimated parts of the Quweira Sandstone succession in the Al Ula area are stated for different study areas (lines of section), as observed (Figure 4.51) (see Figure 3.2, P. 60 and Figure 3.3, P. 61 for lines of section in the Al Ula study area). These "parts" are estimated by their stratigraphic position, some sedimentological features and changes in facies associations.

Area U1 (measured sections U101 through U103) contains the basal contact of the Quweira Sandstone with the Upper Siq Sandstone, and it is estimated to cover the lower and the middle parts of the Quweira Sandstone in the Al Ula area. Facies distribution in these measured sections shows an overall dominance of fluvial-dominated facies associations (FA 1 and 2). Area U2 (measured sections U201 and U202) contains parts of the lower Quweira and most of the middle part of that sandstone unit. The facies distribution shows a dominance of fluvial-dominated I facies association (FA 1), with a relatively increased percentage of fluvial-dominated II facies association (FA 2), and minor presence of high-energy tidally-dominated facies association (FA 4). Area U3 (measured sections U301 through U305) covers most parts of the Quweira Sandstone in the Al Ula area from its basal contact with the Upper Siq Sandstone to a point considered to be near its upper contact with the Saq Sandstone. The facies distribution in this area shows a significant dominance by fluvial-dominated facies associations (FA 1 and 2). Area U4 (measured section U401) is estimated to cover parts of the middle and possibly all of the upper part of the Quweira Sandstone in the Al Ula area. The facies distribution also shows dominance by fluvial-dominated facies associations (FA 1 and 2). Deformed sandstone facies (11 through 13) are found variably-distributed throughout measured sections in the Al Ula area.

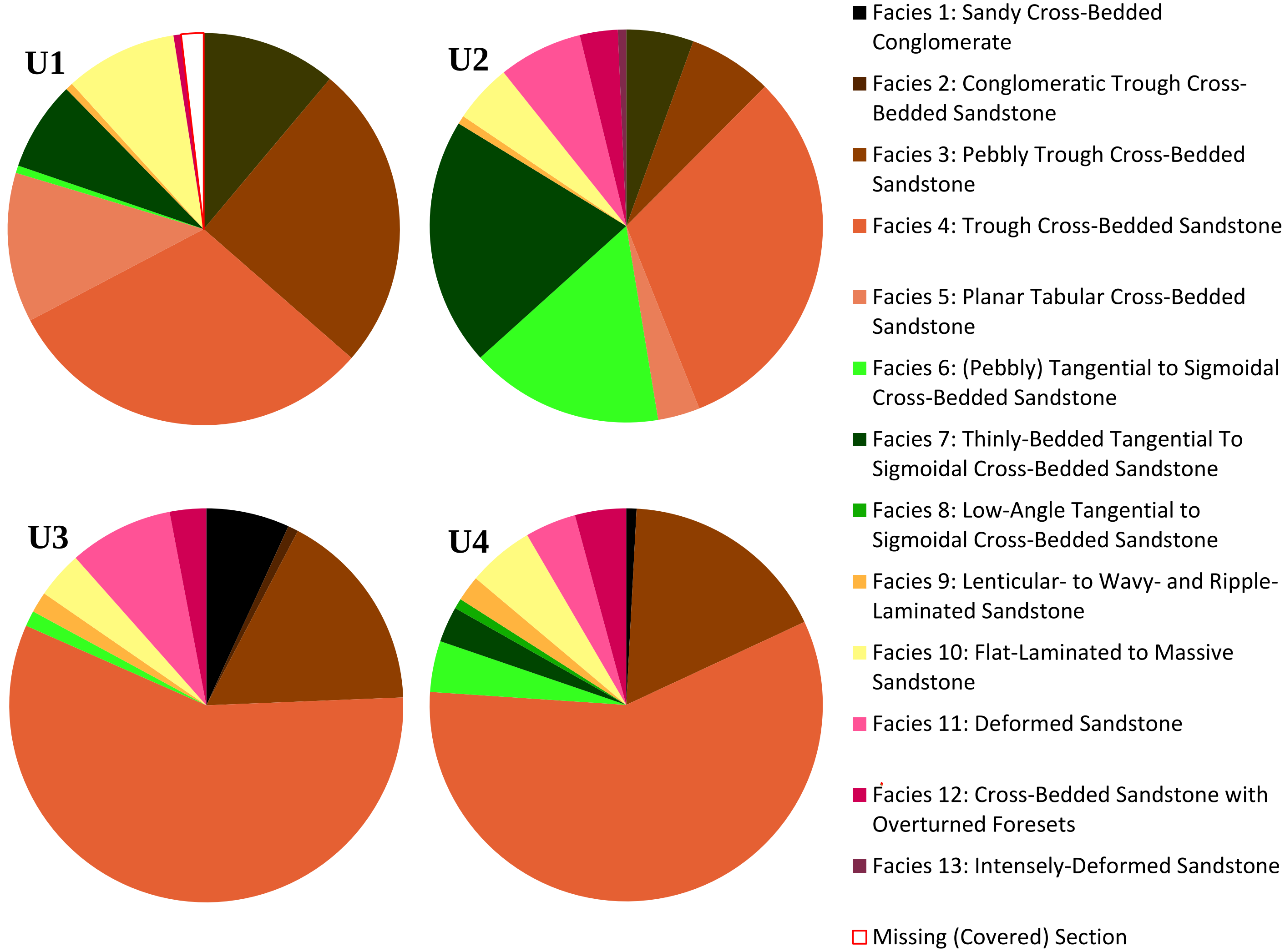


Figure 4.51: Facies distribution within the Quweira Sandstone in the Al Ula area as observed in different lines of section; defined by the different composite measured sections (see Chapter 5 for further discussion).

3. Facies Distribution in the Saq Sandstone in the Al Ula Area

The limited data from the Saq Sandstone in the Al Ula area shows a facies distribution which already has been discussed previously in this section (Figure 4.49), showing limited fluvial-dominated facies associations (FA 1 and 2), in addition to increased presence of deformed sandstone facies association (FA 6).

4.1.3.2 Facies Distribution in the Tabuk Area

Investigation of the Cambro-Ordovician succession in the Tabuk area allowed for measuring sections in the Siq, Quweira and Saq Sandstones; Figure 4.48 shows the overall facies distribution in this study area.

Figure 4.52, shows the facies distribution of different sandstone units in the Tabuk study area. The Siq Sandstone (considered only to be represented by the Upper Siq Sandstone in the Tabuk area; see section 5.2.1, P. 222) shows fluvial-dominated I facies association (FA 1) and increased footage of fluvial dominated II facies association (FA 2). Each facies group comprises about 25% of the overall measured footage in this sandstone unit in the Tabuk area. In the Quweira Sandstone, a combination of fluvial dominated II and high-energy tidal-dominated facies associations are observed (FA 2 and 4). The local catastrophic deposition (?) debris flow facies association (FA 7) is also observed in this part of the succession. The Saq Sandstone shows dominance by fluvial-dominated facies associations (FA 1 and 2), with dominance of Facies 5 deposits (planar tabular cross-bedded sandstone) in comparison with all other sandstone units observed in both study areas, which are dominated by in-channel fluvial deposition. Facies 1 and 2 are not present in the succession studied in the Tabuk area, and deformed facies are common and randomly distributed throughout the succession.

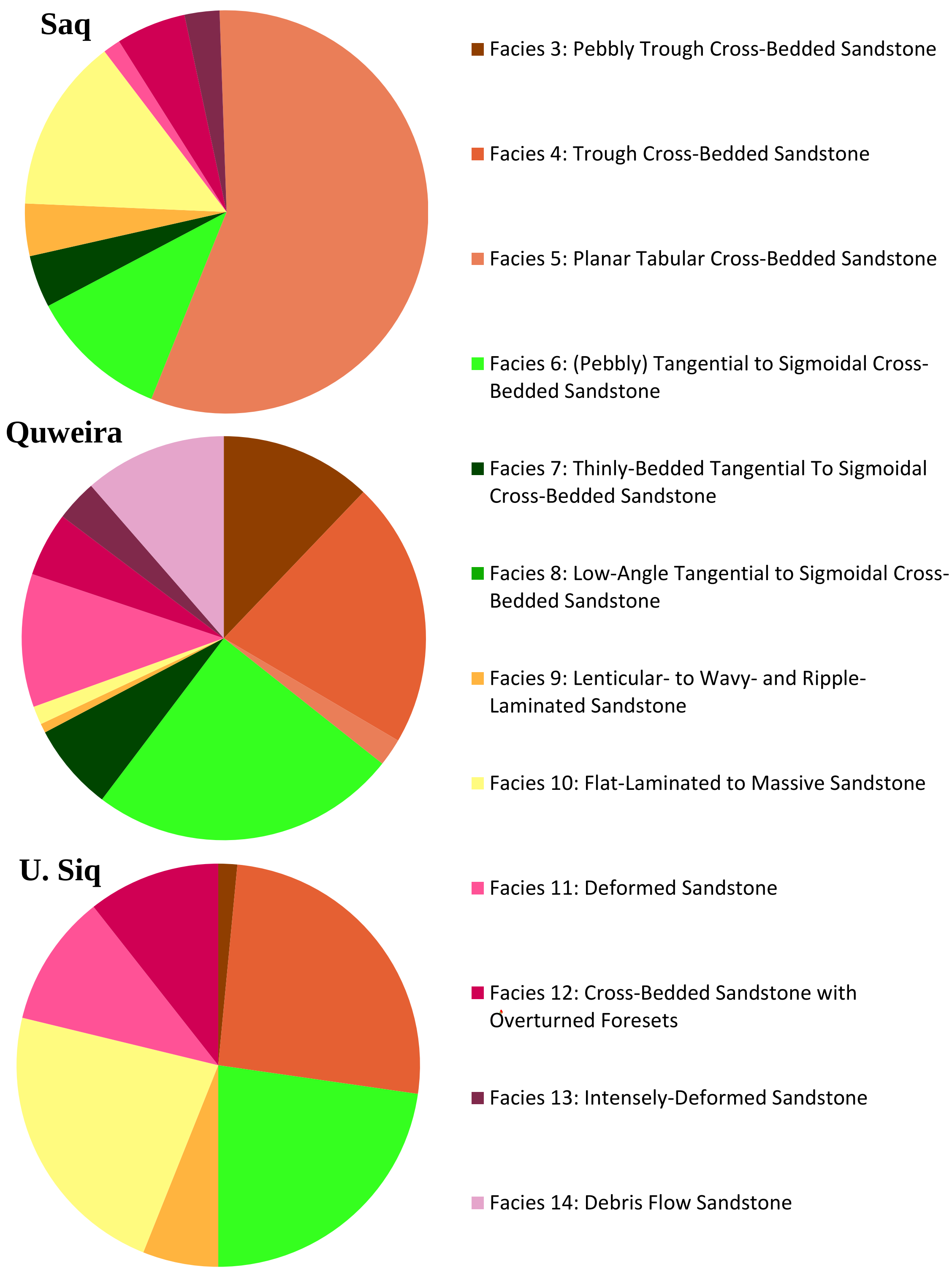


Figure 4.52: Facies distribution in the three sandstone units; the Upper Siq, Quweira and Saq Sandstones in the Tabuk area.

4.1.3.3 Facies Distribution Variations between the Al Ula and Tabuk Areas

Comparisons of the distribution of facies and facies associations among all the different sandstone units in both the Al Ula and Tabuk areas clearly show more tidally-influenced and tidally-dominated deposition in the Tabuk area measured sections. The Lower and Middle Siq Sandstones are missing in the Tabuk area (see section 5.2.1, P. 222), and therefore a comparison for these sandstone units cannot be made.

Specifically, the Upper Siq Sandstone shows deposition that is dominated by fluvial-dominated facies associations (FA 1 and 2) in both the Al Ula and Tabuk areas (Figure 4.50 and Figure 4.52). However, fluvial dominated II facies association (FA 2) shows more abundance in the Tabuk area compared to the Al Ula area, indicating increased tidal influence at the Tabuk locality. The Quweira Sandstone displays similar prominent fluvial-dominant facies associations (FA 1 and 2) in the Al Ula area (Figure 4.49 and Figure 4.51), whereas these sandstones show increased tidal influence in the Tabuk area, displaying a combination of fluvial dominated II and high-energy tidally-dominated facies associations (FA 2 and 4), in addition to the local catastrophic deposition (?) debris flow facies association (FA 7) (Figure 4.52). The Saq Sandstone shows fluvial-dominated facies associations (FA 1 and 2) in both the Al Ula and Tabuk areas, with variations in the dominating facies (Figure 4.49 and Figure 4.52). In the Al Ula area, the fluvial facies are characterized by primarily in-channel deposits (Facies 3 and 4), whereas the fluvial facies in the Tabuk area are mostly illustrated by sand-flat deposits (Facies 5). The Saq Sandstone in the Al Ula area also shows deformed facies association (FA 6).

4.2 Paleocurrent Data Analysis

A total number of 270 dip-direction (dip azimuth) measurements of cross-bedding were collected in both the Al Ula and Tabuk study areas to analyze the paleocurrent directions. These measurements were collected from all sandstone units and described facies where possible. Measurements were segregated in different datasets with respect to the study areas near both Al Ula and Tabuk, their line of section, sandstone unit and facies group (Appendix A). This dataset was manipulated to produce a number of rose diagrams, which illustrate all data collected within each dataset showing the vector mean direction. These readings allow consideration of any changes in paleocurrent directions throughout the succession in different localities, how this might relate to possible changes in sedimentary source area and how each composite section in the Al Ula and Tabuk areas possibly fit the overall depositional setting. Figure 4.53 shows the overall paleocurrent direction measurements collected in both the Al Ula and Tabuk study areas.

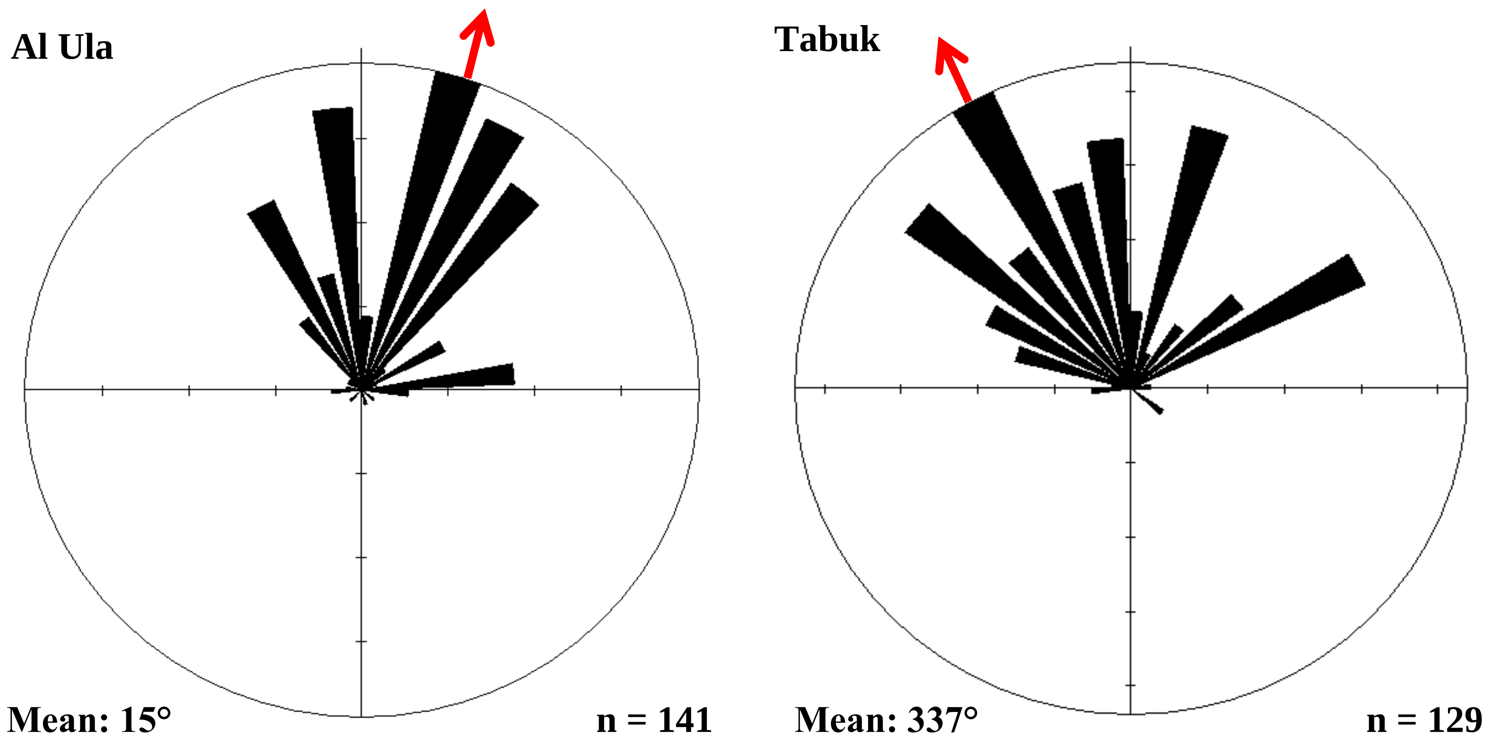


Figure 4.53: Rose diagrams representing paleocurrent direction data collected in both study areas near Al Ula and Tabuk from all sandstone units. Vector mean values and number of measurements are displayed.

4.2.1 Paleocurrent Data Analysis in the Al Ula Area

The three sandstone units of the Cambro-Ordovician succession in the Al Ula study area show variations in paleocurrent direction throughout the succession. Figure 4.54 displays rose diagrams of data collected from the Siq, Quweira and Saq Sandstones in the Al Ula area. Paleocurrent direction analysis from the different sandstone units studied in this area indicates a change in vector mean paleocurrent direction from the NNW in the Siq Sandstone, through NNE in the Quweira Sandstone and ultimately NE in the Saq Sandstone. Due to its stratigraphic complexity in comparison with the other two units, the Siq Sandstone will be discussed further in this section.

In Figure 4.54, paleocurrent direction analysis from data collected in the Quweira Sandstone successions in the Al Ula area indicates a dominant flow direction towards the NNE, with minor variations between E and NW, at a calculated vector mean of N15°E. Paleocurrent direction analysis of the Saq Sandstone dataset shows dominant flow towards the NE directions, showing minor variations between E and N, with a calculated vector mean of N42°E.

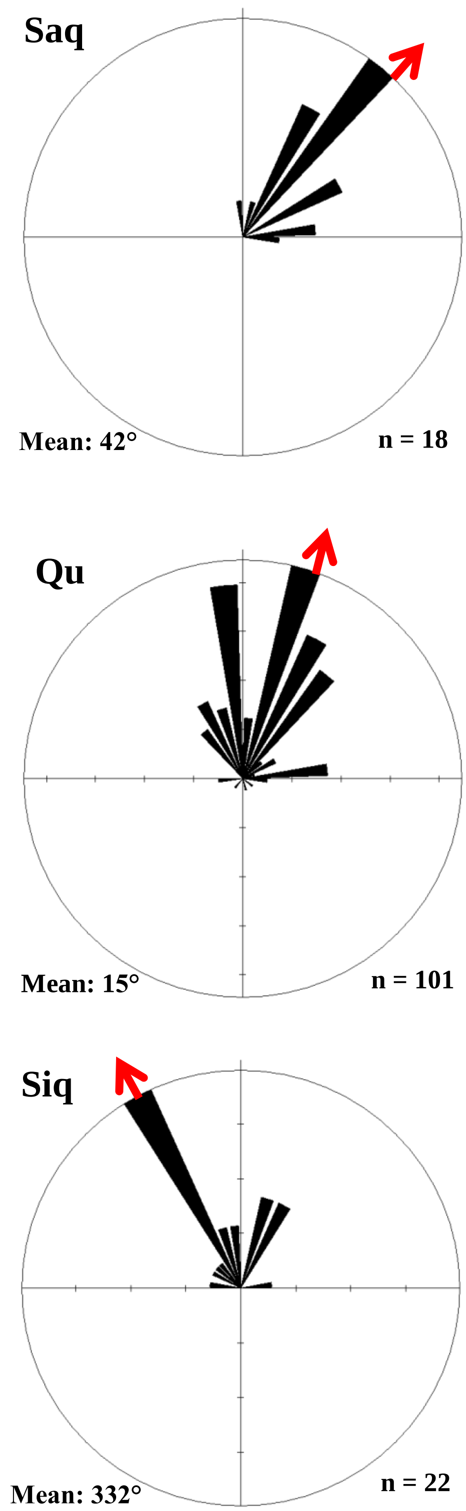


Figure 4.54: Rose diagrams representing paleocurrent direction data collected from the overall Siq, Quweira and Saq Sandstones in the Al Ula study area. Vector mean values and number of measurements are displayed.

- **Paleocurrent Analysis of the Siq Sandstone in the Al Ula Area**

Paleocurrent direction data collected from the Siq Sandstone outcrops in the Al Ula area were further subdivided into three additional datasets based on the partitioning of this unit into three sub-units (see CHAPTER 1, P. 1).

Figure 4.55 shows three rose diagrams that display paleocurrent direction data collected from the Lower, Middle and Upper Siq Sandstones in this area. The available data from the Lower Siq Sandstone suggests a consistent flow direction towards the NW. Data collected from the Middle Siq Sandstone indicates no major shift with respect to the underlying unit with a calculated vector mean of N342°E towards the NNW and minor variations between W and E. The overlying Upper Siq Sandstone, on the other hand, shows a marked change in flow direction towards the NE, with a calculated vector mean of N13°E. These data suggest a shift in paleocurrent direction in this succession that occurred at the base of the Upper Siq Sandstone and continued through into the Quweira and Saq Sandstones in the Al Ula area (Figure 4.54).

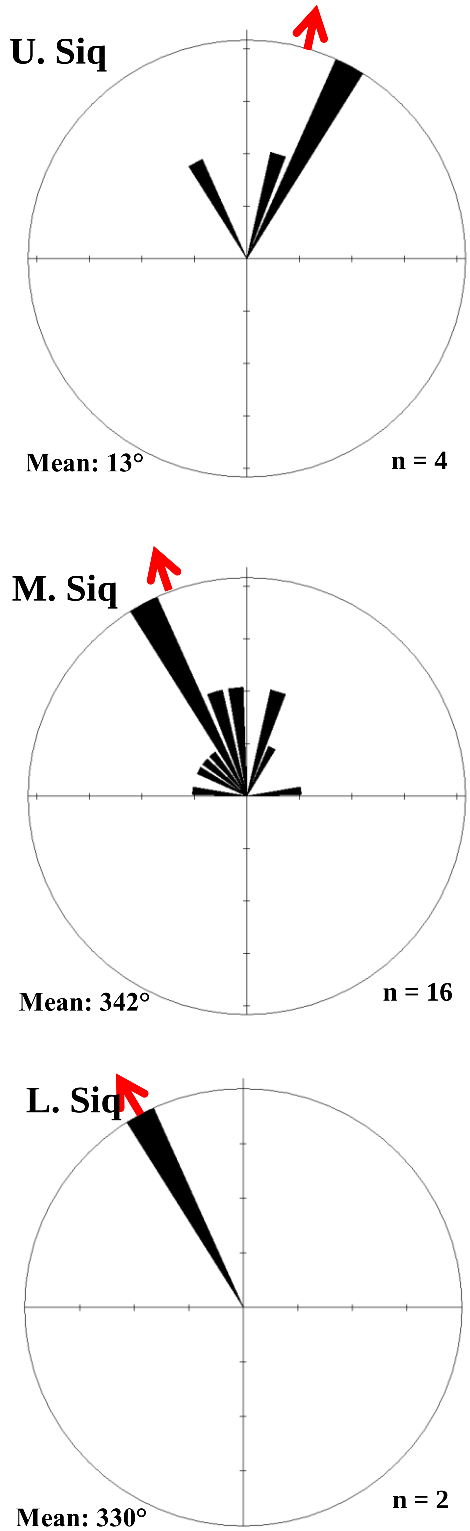


Figure 4.55: Rose diagrams representing paleocurrent direction data collected in the Lower, Middle and Upper Siq Sandstones. Vector mean values and number of measurements are displayed.

4.2.2 Paleocurrent Data Analysis in the Tabuk Area

Similar to the Al Ula area, the three sandstone units of the Cambro-Ordovician succession in the Tabuk area show notable variations in paleocurrent direction throughout the succession. Figure 4.56 displays rose diagrams of paleocurrent data collected in this area from these three units. These readings indicate a subtle change in paleocurrent direction towards the NNW in the (Upper) Siq and Quweira Sandstones, with an apparently significant change in flow direction towards the ENE in the Saq Sandstone.

Paleocurrent direction data collected in the (Upper) Siq Sandstone in the Tabuk area illustrate a wide distribution of flow directions ranging from ENE, NNW, WNW and SW, with a vector mean of N323°W (Figure 4.56). Similarly, the Quweira Sandstone data indicate a vector mean direction of N334°W and readings vary between NE and WSW, with more concentration in the NNW and NW directions. Paleocurrent direction analysis of measurements collected in the Saq Sandstone in the Tabuk area indicates a major change in flow direction towards the NNE and ENE with a calculated vector mean of N40°E.

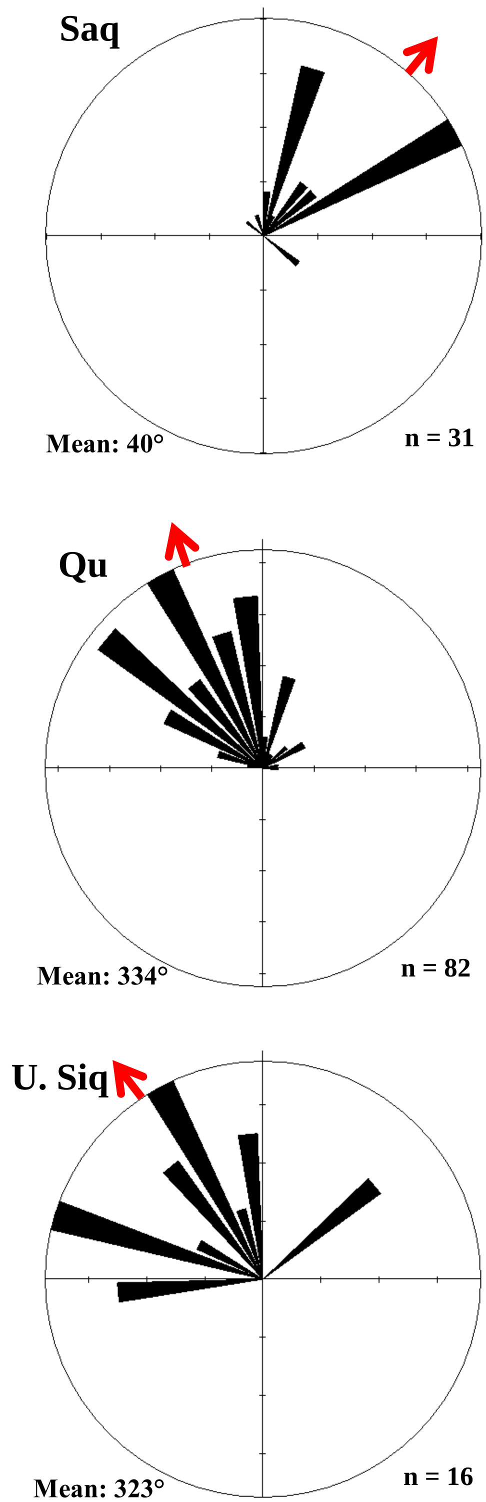


Figure 4.56: Rose diagrams representing paleocurrent direction data collected in the (Upper) Siq, Quweira, and Saq Sandstones in the Tabuk area. Vector mean values and number of measurements are displayed.

4.3 Petrographic Studies

A total of 141 thin sections of samples collected from the sandstone units in both study areas near both Al Ula and Tabuk were described and point counted at 300 points per thin section. The point count data are presented in Appendix A. This section summarizes the results of these descriptions and the analysis that followed the point count of the samples.

4.3.1 Thin Sections Descriptions

This study revealed the presence of a number of detrital constituents which include: monocrystalline quartz, polycrystalline quartz, potassium-feldspars, plagioclase, rock fragments, and micas. Authigenic components were also described, in addition to comments regarding porosities and diagenetic alterations, but not included in further implications in the study (and in CHAPTER 5 Discussion, P. 194).

4.3.1.1 Detrital Components

These components were identified and studied in thin sections prepared for this study. Each detrital component is described in detail below.

1. **Monocrystalline Quartz:** This is the most abundant detrital grain type among the studied samples. Quartz grain sizes vary between the ranges of generally <50-200 µm, 300-800µm, and 600-1200< µm. Since some samples demonstrate a bimodal distribution

of grain size, they combine more than one range of grain sizes presented. These grains show variable sorting from moderately- to poorly-sorted and well- to moderately-sorted in different parts of the succession. Monocrystalline quartz grains are generally sub-angular to sub-rounded, and also rounded to well-rounded in places. The grains are identified by their grey birefringence in cross nicols (XPL) and commonly show straight extinction. In trace to rare examples, grains show undulatory extinctions. The varying properties of monocrystalline quartz are illustrated in Figure 4.57.

2. **Polycrystalline Quartz:** These grains are made of aggregates of quartz crystals. Similar to monocrystalline quartz, polycrystalline quartz grains were identified by their low birefringence and multiple, sharp to undulatory grey extinctions in XPL. Grain sizes in this component are commonly coarser compared to monocrystalline quartz. They occur in the grain-size range of 600-1200< µm (Figure 4.57). In few examples, polycrystalline quartz grain-sizes reach up to 2.0 mm (Figure 4.58). In contrast to monocrystalline quartz grains, polycrystalline quartz grains are commonly sub- to well-rounded. In many examples, the crystals in these grains show a preferred alignment, or foliation (Figure 4.58).

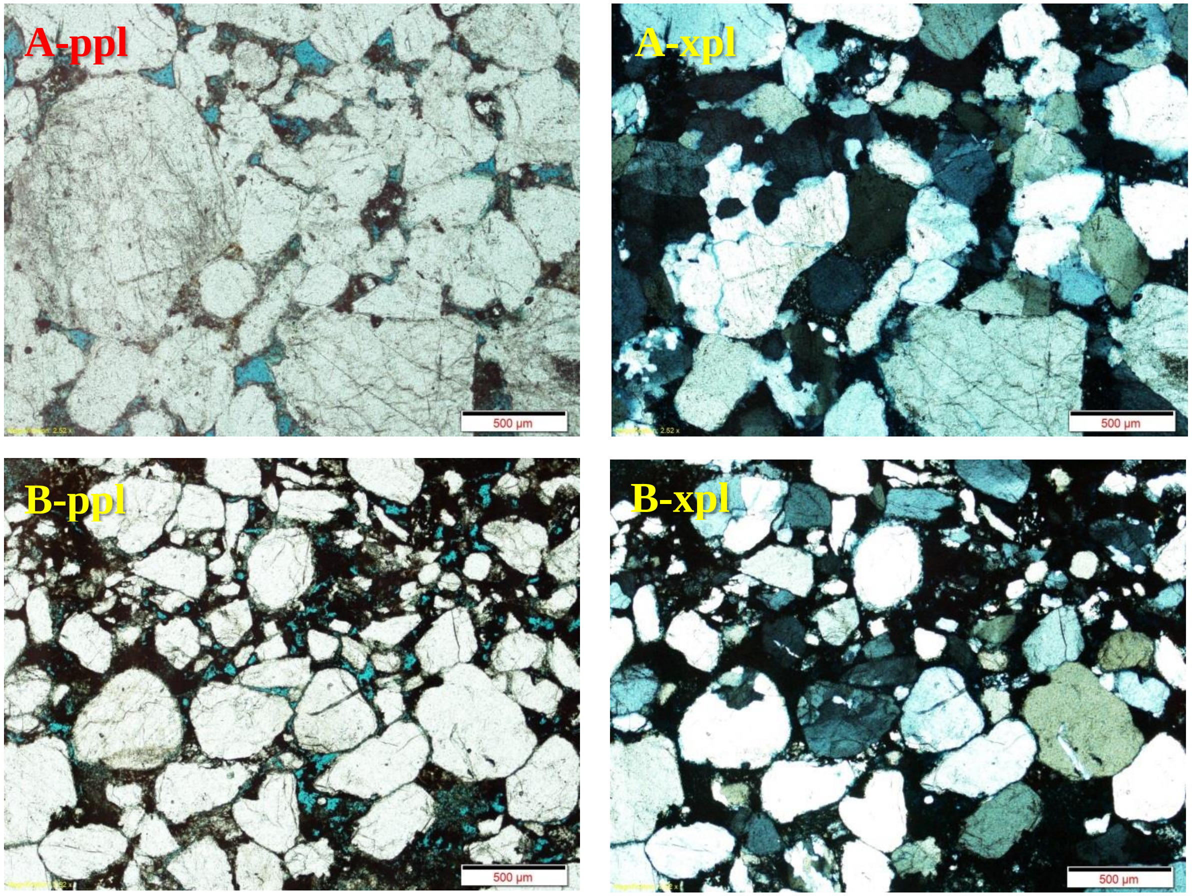


Figure 4.57: Two thin sections showing both monocrystalline and polycrystalline quartz grains of different sizes and shapes, showing both straight and undulatory extinctions and bounding mud-clast grains (samples A: U102-S4-1; and B: U302-S5 – Appendix A).

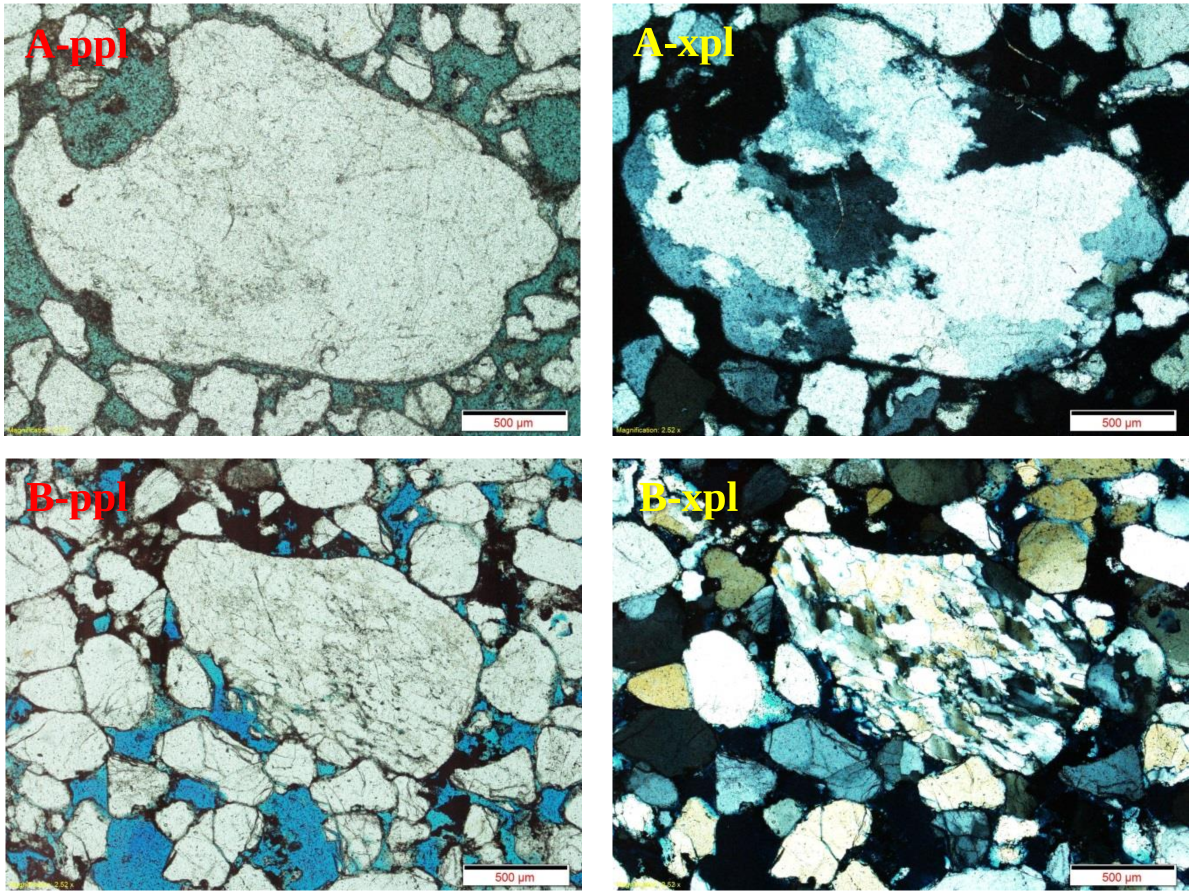


Figure 4.58: Two thin sections showing examples that illustrate the presence of polycrystalline quartz in some of the studied thin sections, showing very coarse grain size (A) and the effect of strain (B) (samples A: U305-S6; and B: T102-S2 – Appendix A).

3. Alkali-Feldspars: These grains are identified by their low birefringence, Carlsbad (orthoclase) twinning and/or “cross-hatch” (microcline) twinning, characteristics that were observed in studied thin sections. Some of these grains were stained by Na-cobaltinitrite to help identify K-feldspars (see section 3.3.2, P. 67). K-feldspar grain sizes are mainly found within two ranges of 50-200 µm, and 200-600 µm. Their shapes are found in general to be sub-angular to sub-rounded. Grains are identified either as orthoclase or microcline feldspars. Orthoclase feldspar grains are identified by the presence of Carlsbad twinning in low-birefringence grains, whereas microcline grains display polysynthetic, “cross-hatch,” twinning in low-birefringence grains (Figure 4.59). Other kinds of alkali feldspars, such as sanidine and anorthoclase, were not recognized in studied thin sections. This could be a result of their absence or later-stage chemical dissolution observed in some of these grains (Figure 4.59).

4. Plagioclase-Feldspars: These grains are identified by their low-birefringence and distinctive, parallel albite twinning in studied thin sections. They were found in only trace amounts in all studied thin sections (less than 1.00%). Therefore, their qualitative properties could not be appropriately described and characterized.

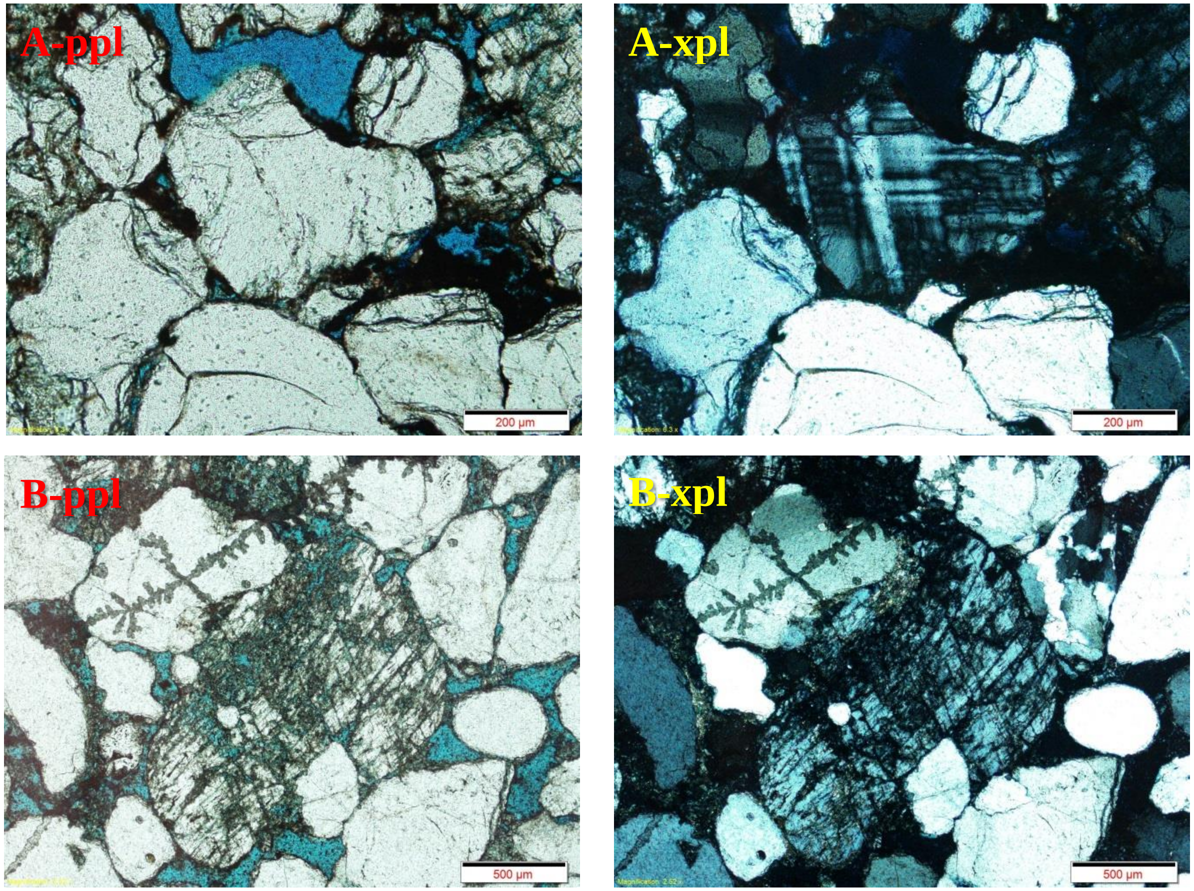


Figure 4.59: Examples of K-feldspar grains showing microcline-extinction (A) and the effect of dissolution (B) (samples A: U101-S1; and B: U101-S8 – Appendix A).

5. **Rock Fragments:** lithic constituents recognized in studied thin sections appear to be mostly of a sedimentary source. However, some chert grains may suggest a metasedimentary source. Mud-clasts, recognized as grains with definite boundaries (Figure 4.60), are the dominant lithic component, with trace presence of coarser-grained sandstone clasts and cherts. Lithic fragments in thin sections generally showed epiclastic, sand-size, intraformational mud clasts comprising clay- to sand-sized inclusions. Mud clast observed are commonly bounded and deformed by adjacent (quartz) grains as a result of compaction. They are thus commonly "squeezed" among the adjacent grains, forming a "pseudo-matrix" in the pore space (Figure 4.60). Due to this ductile, pore-filling nature, appropriate grain-size measurements were disregarded. Chert grains and sandstone clasts occur only rarely in the thin sections studied, observed in a variety of different sizes and shapes (Figure 4.61). Trace amounts of zircon crystals were also observed in thin sections. Chert grains were counted as part of rock fragments in point counting, following the sandstone classification of Folk et al. (1970).

6. **Mica:** These flaky grains are identified by their high-birefringence and colorful interference in XPL. Dominated by the presence of muscovites, and less commonly biotites, they are mainly found in trace amounts, most commonly in finer-grained sandstones (Figure 4.62).

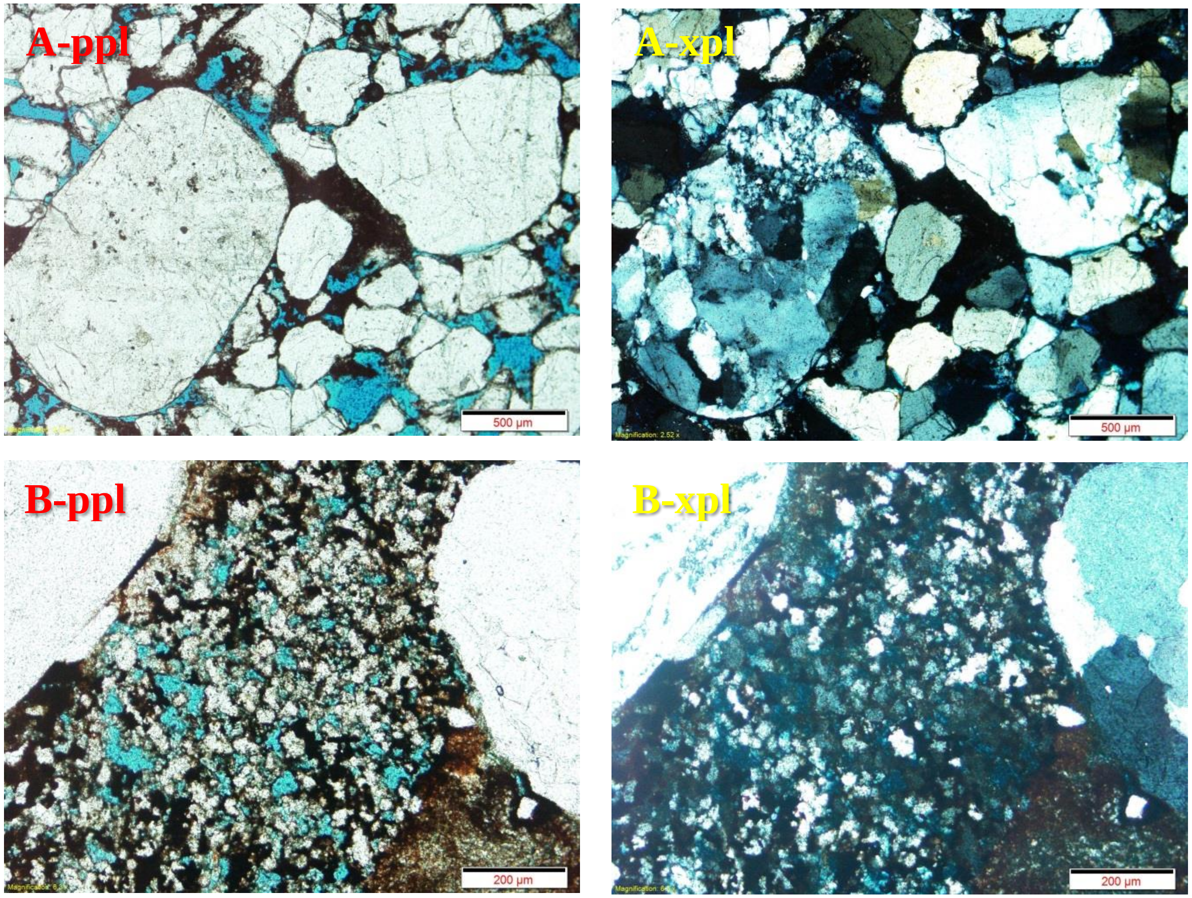


Figure 4.60: Different examples of mud clasts in thin sections showing (A) the ductile deformation effect of adjacent quartz grains, and (B) the effect of dissolution and intragranular-porosity enhancement in a more silty rock fragment (samples A: T102-S2; and B: U301-S4 – Appendix A).

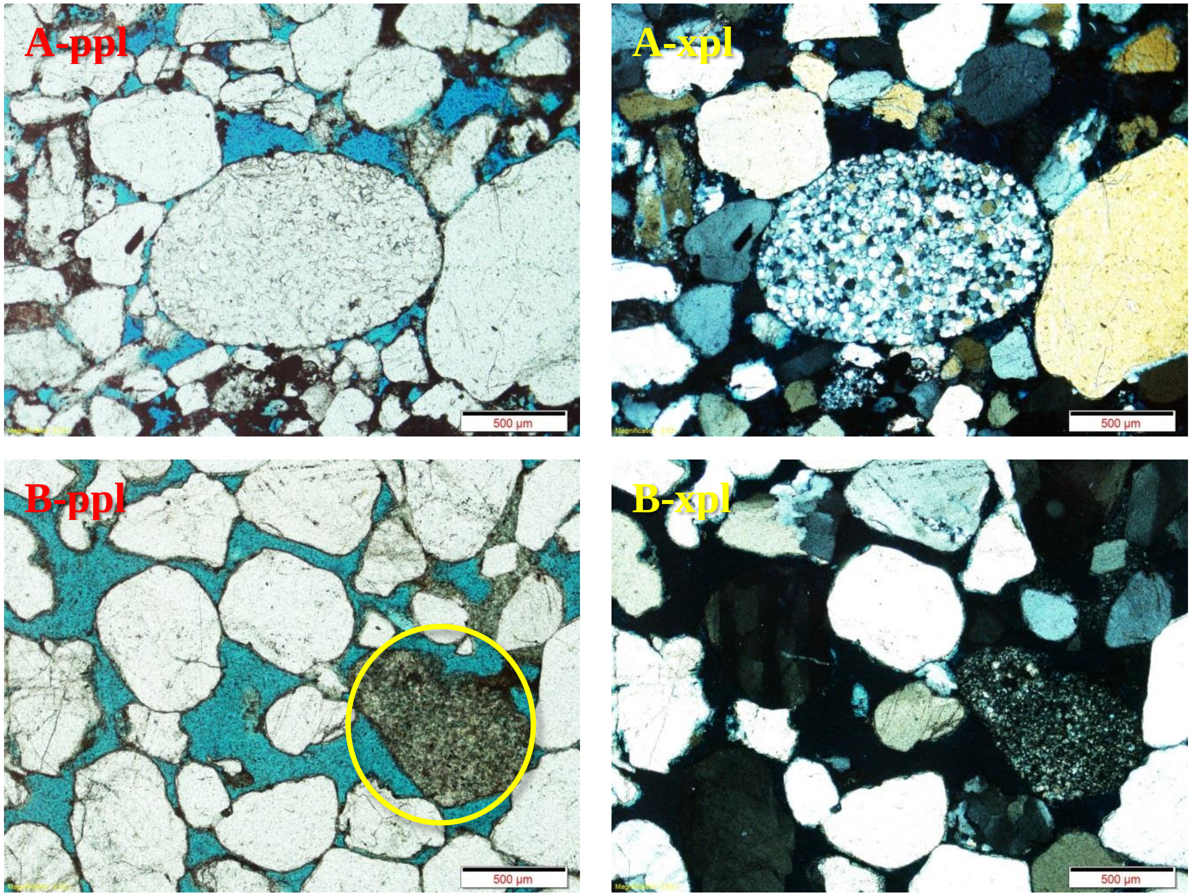


Figure 4.61: Two thin section examples showing (A) a well-rounded sandstone clast, and (B) an angular chert grain in a porous sandstone sample (samples A: T102-S2; and B: U103-S1-2 – Appendix A).

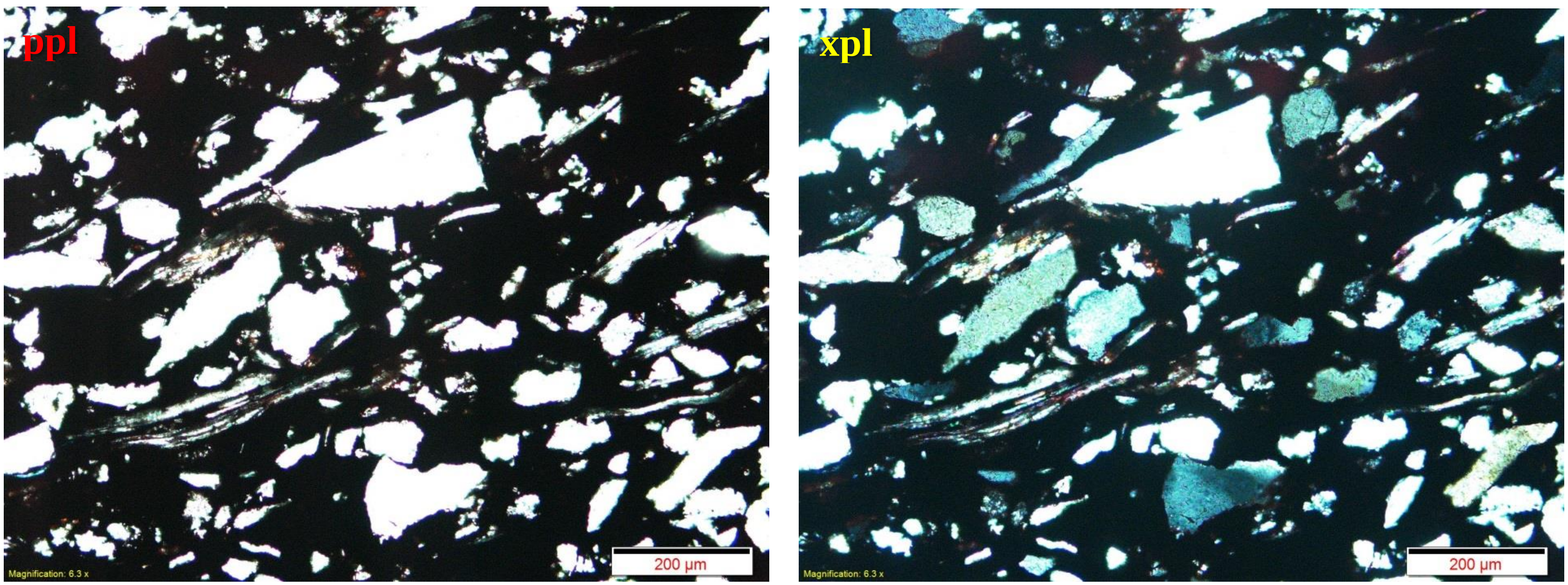


Figure 4.62: Thin section example showing abundance of mica grains (muscovite) in a very fine-grained, iron oxide-cemented sandstone (sample T105-S8-1).

4.3.1.2 Diagenetic Alterations

Diagenetic components are only found in small amounts in the studied thin sections, compared to detrital components. These components are not inclusively present in all samples. The description of these components is limited when using conventional microscopic techniques. The following includes brief descriptions of these components.

Kaolin-Clays: Recognized by their flake-like grains, these kaolin clays are often observed as a result of alterations of unstable detrital components, mainly feldspars. Clays are mostly found within sites of chemical dissolution and intra-granular porosity in thin sections. While they are mostly observed in very small-sizes (1-3 μm), in general they cannot be investigated in more details due to the low depth of resolution of conventional petrography. In places, kaolinite occurs as more coarsely-crystalline, pore-filling aggregates, or “booklets” (Figure 4.63), and in a rare example displays a distinctly vermiform habit.

Quartz Overgrowth: Observed in both mono- and polycrystalline quartz grains, quartz overgrowth generally occurs in only trace amounts. It either occurs as partial or complete cements of clean quartz grain surfaces and rims (Figure 4.64). Variations in silica cements observed in samples are possibly affected by increasing amounts of lithics and iron-oxide cements. Coating of quartz grains by these components perhaps affects the development of quartz overgrowth in studied thin sections.

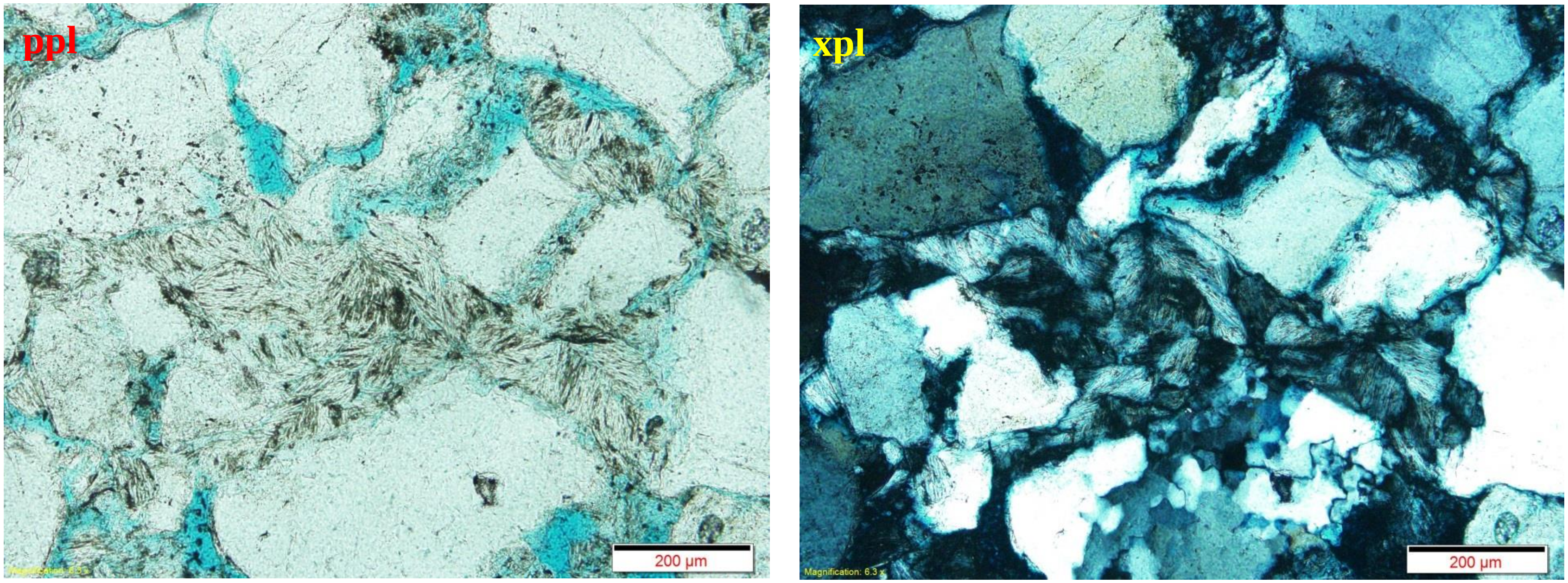


Figure 4.63: Thin section example showing pore-filling, well-developed kaolinite aggregates in a sandstone sample (sample U401-S9 – Appendix A).

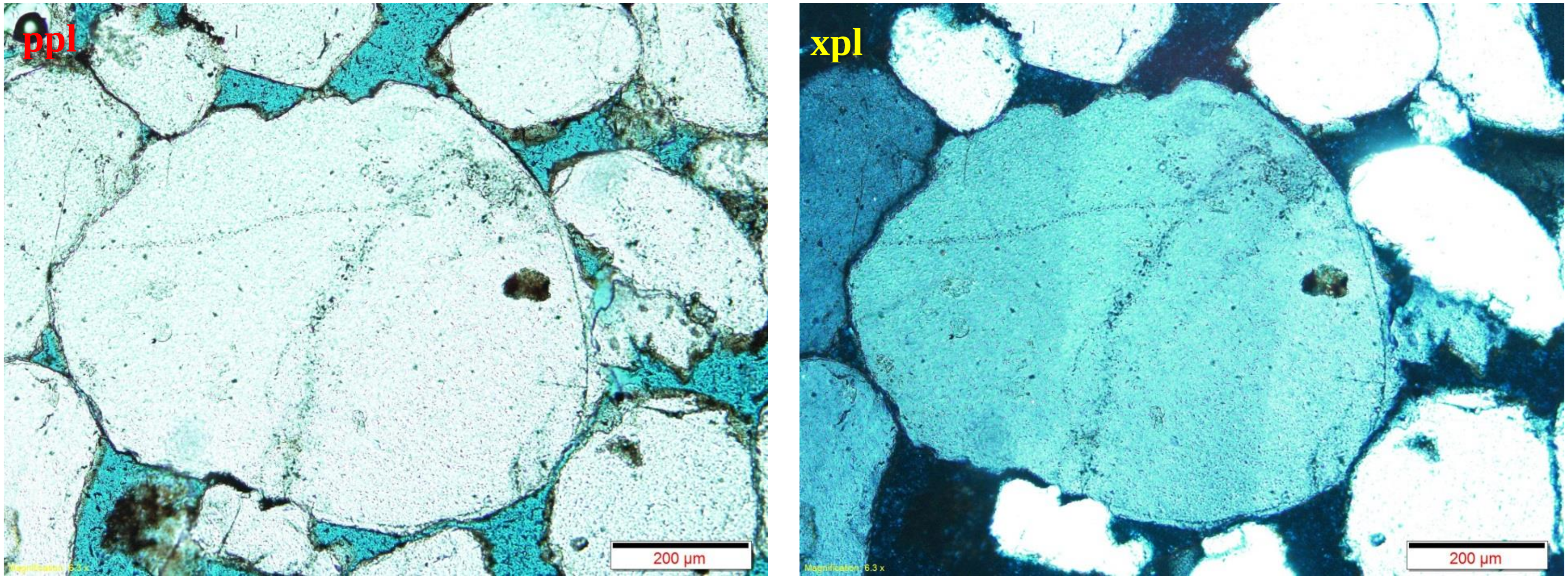


Figure 4.64: Thin section example showing quartz overgrowth in a monocrystalline-quartz grain, which also shows the possible effects of both iron-oxide cementation and compaction (sample T105-S6).

Iron-Oxide Cements: These are red and reddish-brown, and yellow cements in places, and are found in variable abundance throughout studied thin sections. Stains are often found partially to fully coating quartz and mud clasts (Figure 4.61 and Figure 4.65). In some thin sections, red-cements dominate the sample color and contribute to the deterioration or elimination of porosity (Figure 4.62). In some quartz grains, cement-coating is commonly observed as red, thin, full-coating of grains, or as yellow-rim, partial-cementation (Figure 4.65). It is suspected that the presence of these cements prevents the development of quartz overgrowth in both monocrystalline and polycrystalline quartz grains. In rock fragments, cements are observed as spotty red-cement or fully red-stained mud clasts, which prevents thorough descriptions. In rare examples, dark-red, mostly angular-shaped opaque minerals were observed in sandstone samples (Figure 4.66). They are possibly oxidized magnetite grains that cause the red-color staining in some of the studied samples.

Matrix: It is only observed in a very small number of samples that are generally finer-grained, silty sandstones. Matrix observed in these samples is possibly associated with minor alterations of sedimentary rock fragments (mud clasts) in samples. It is also observed that the presence of matrix deteriorates or eliminates porosity in these samples

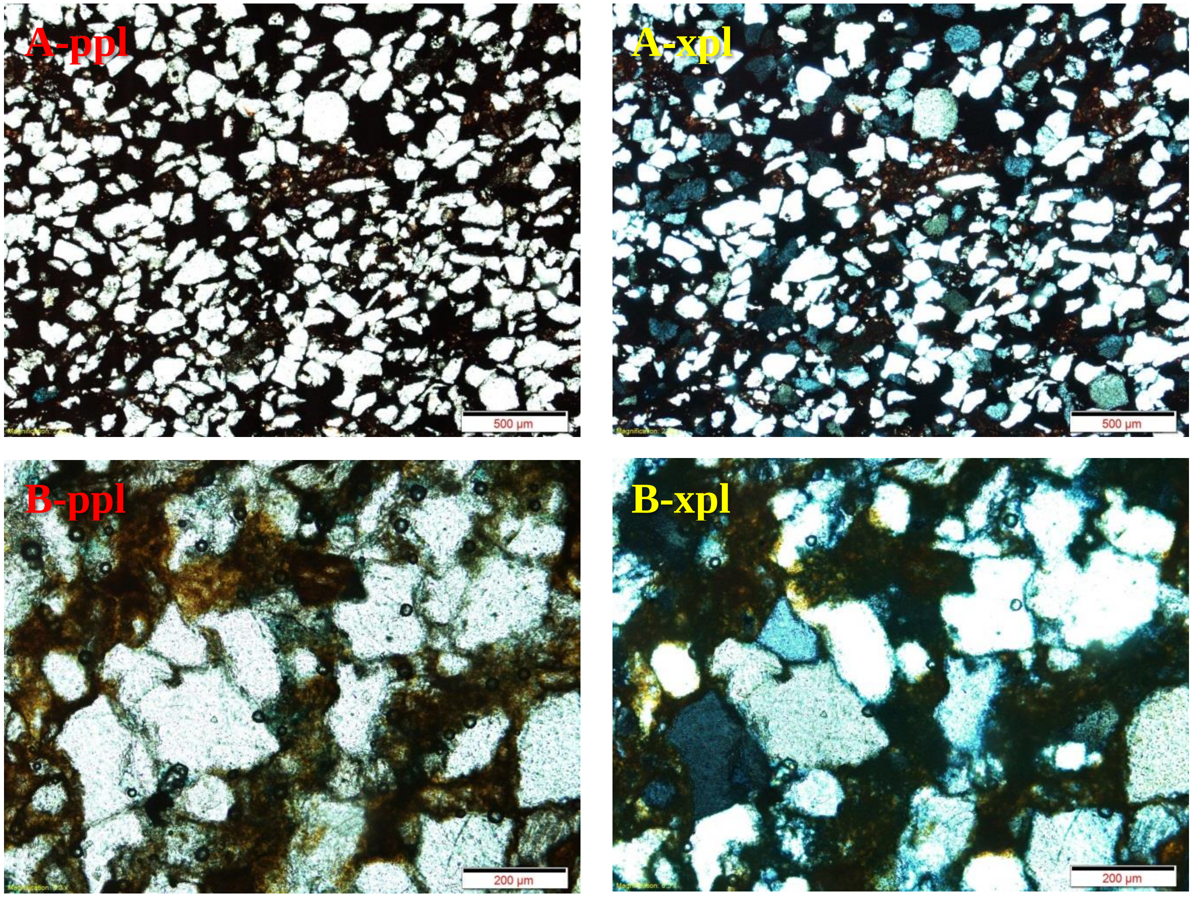


Figure 4.65: Thin section examples of (A) extensive red iron-oxide cementation and (B) partial yellow iron-oxide cementation, showing variable effect on possibly quartz overgrowth and porosity (samples A: U303-S4; and B: U305-S8-c – Appendix A).

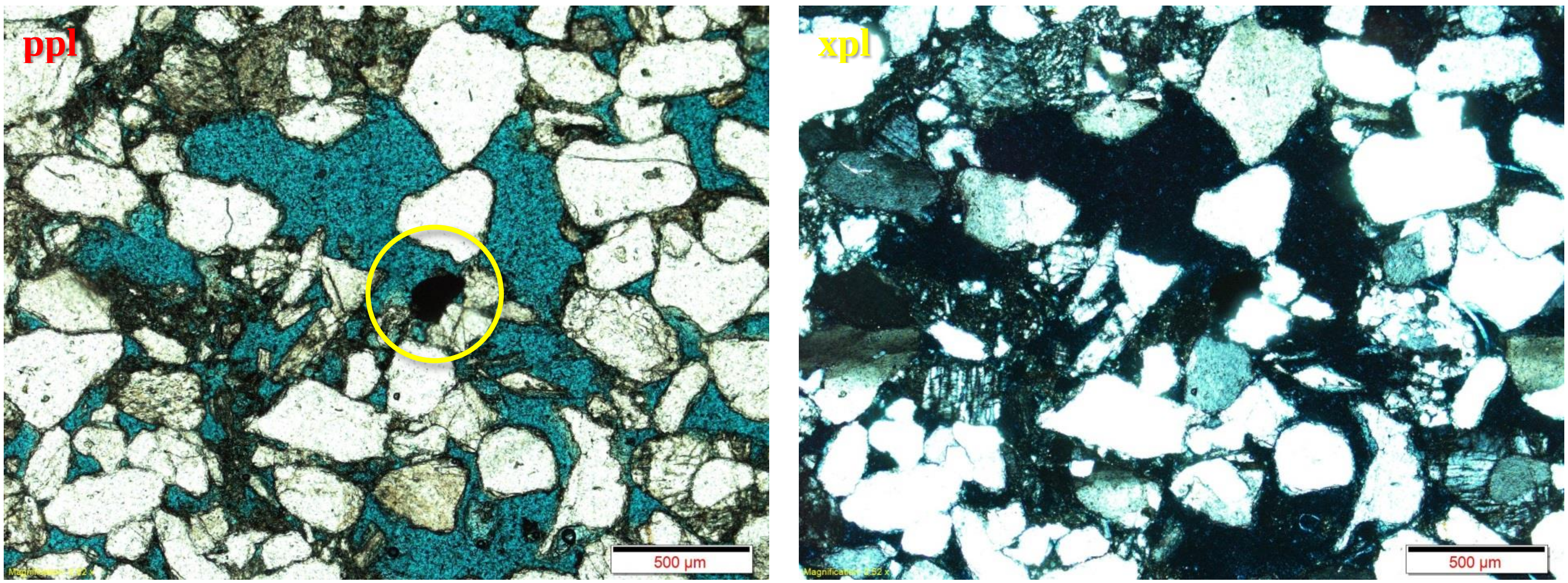


Figure 4.66: Thin section example showing an opaque mineral (circled) that possibly causes staining and iron-oxide cementation in sandstone samples (sample U101-S5 – Appendix A).

4.3.1.3 Compaction

Compaction appears to have altered the grain-packing in variable but limited degrees in studied thin sections. Generally sub-angular to sub-rounded quartz grains display packing organization and rearrangement in thin sections as a result of mechanical compaction (Figure 4.57 and Figure 4.64). In rare cases, quartz dust is observed and could indicate minor brittle deformation of grain-boundaries. Furthermore, evidence of chemical compaction-pressure dissolution are also lacking in studied thin sections. It is suspected that compaction has a minimal impact on the generally high-porosity readings observed.

4.3.1.4 Porosity

Two major types of porosity were distinguished in studied thin sections. Primary, depositional intergranular porosity is found to be the dominating type of porosity in most studied samples (Figure 4.67). On the other hand, secondary, intragranular porosity is limited to dissolution sites of rock fragments and feldspar grains (Figure 4.60). Both porosity types were counted separately through point-count analysis of thin sections. Intra-granular porosity might have been enhanced by diagenesis and weathering of feldspar grains and mud clasts. Furthermore, mechanical compaction might present a minor negative impact on porosity in studied samples. It is observed that both types of porosity are in many places either deteriorated or eliminated by the presence or abundance of iron-oxide cement, and rarely the presence of matrix.

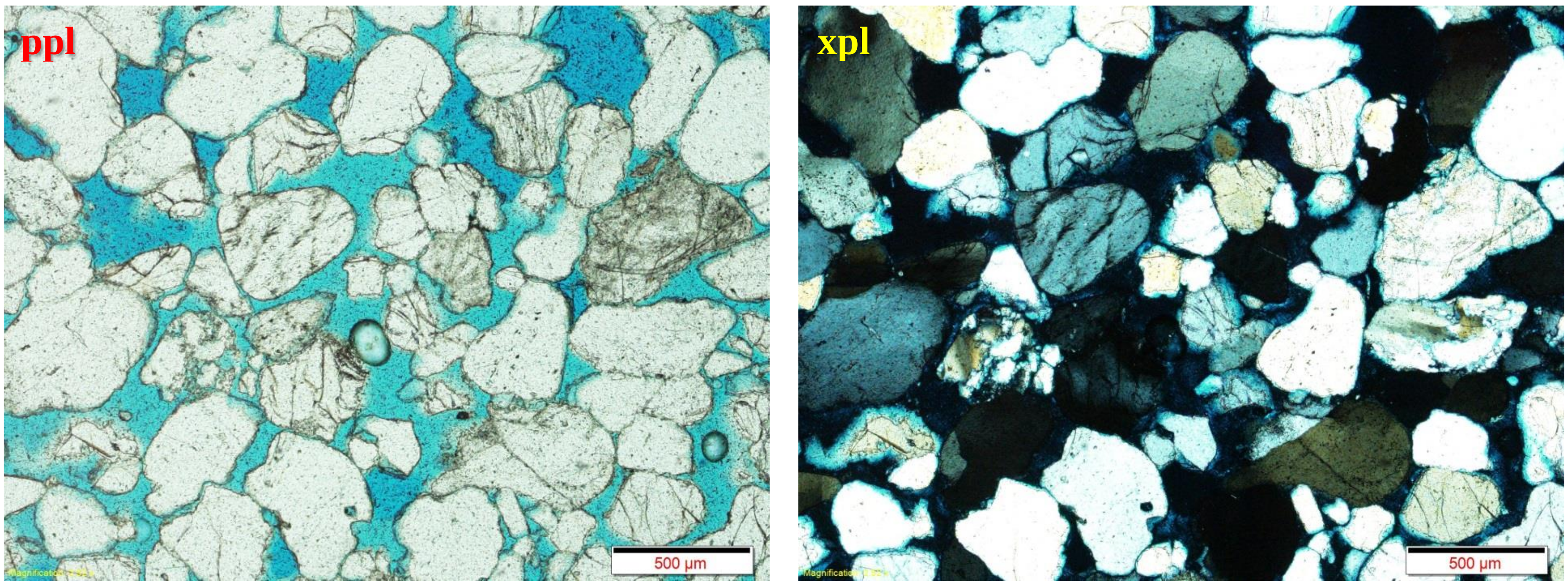
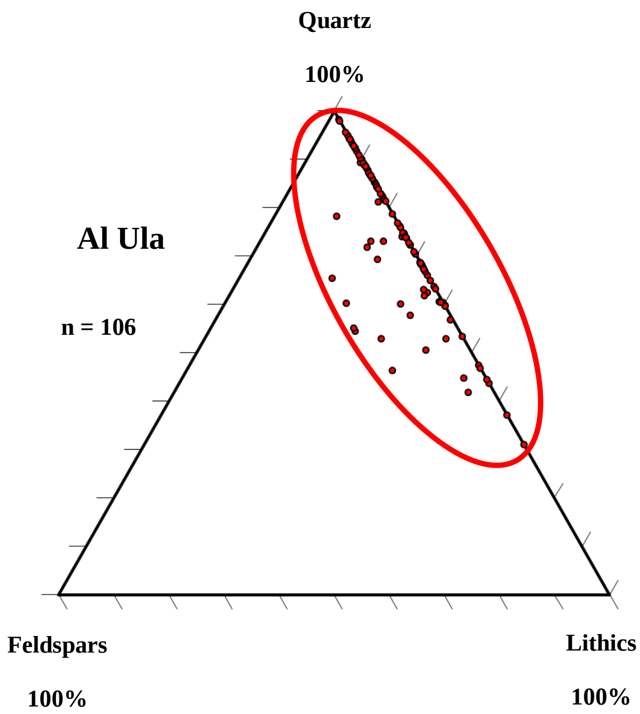


Figure 4.67: Example of enhanced intergranular porosity in a sandstone sample, possibly due to the weathering and elimination of deposited intraformational mud clasts (sample U502-S1 – Appendix A).

4.3.2 Point Count Petrographic Analysis

Thin sections were described and semi-quantitatively analyzed through point counting. The dataset created through this process shows variations in components in all thin sections studied. Point-counted thin sections were then logged and catalogued with respect to locality, area, measured section, sandstone unit and facies (Appendix A). Quartz-feldspar-lithics (QFL) ternary plots were produced to illustrate variations in detrital components in relation to geographic location and sandstone unit. These petrographic datasets have proved most valuable in helping to identify lithostratigraphic variations and trends throughout the studied succession. Sandstone classification of detrital components follows the Folk et al. (1970) classification scheme, as chert grains were counted as lithic-components in this study.

Figure 4.68 shows point-count petrographic analysis from all 141 samples studied in both the Al Ula and Tabuk areas. Petrographic observations from this figure indicate that sandstone compositions in samples collected in the Al Ula area are more variable compared to samples collected in the Tabuk area, and they range between feldspathic litharenite, litharenite, sublitharenite and quartz arenite (Folk et al., 1970). On the other hand, sandstone compositions in the Tabuk area are limited to litharenite, sublitharenite and quartz litharenite with only local occurrences feldspathic component traces.



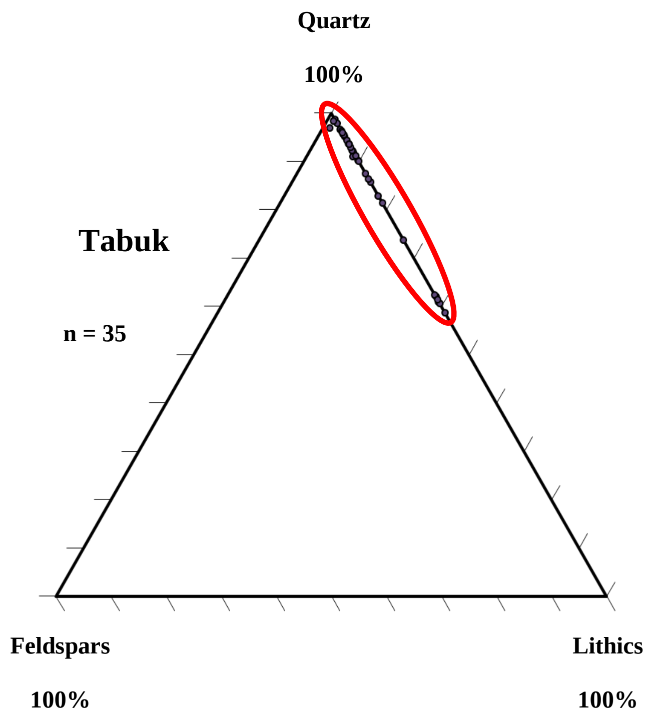


Figure 4.68: QFL (100%) ternary plot illustrating total dataset collected from both the Al Ula and Tabuk areas from all sandstone units, facies and measured sections, highlighting the total number of samples included from each area.

4.3.2.1 Petrographic Analysis in the Al Ula Area

Samples collected from this study area represent the three observed sandstone units of the Siq, Quweira and Saq Sandstones. Data collected from these different units are plotted separately in QFL (100%) ternary plots (Figure 4.69). Petrographic analysis of thin sections collected from the Siq Sandstone in the Al Ula area indicates a range in detrital composition, with variations between feldspathic litharenite, litharenite and sublitharenite (Folk et al., 1970). This characterization is handled in more detail with respect to the different Siq Sandstone units later in this section. Petrographic analysis of data collected from the Quweira Sandstone, through the Saq Sandstone shows an overall gradual maturing from litharenite to quartz arenite, with no feldspars. The dramatic reduction in the arkosic component in comparison with the Siq Sandstone suggests a possible change in sedimentary source, occurring somewhere between the two units. The petrographic data analyzed from the Saq Sandstone in the Al Ula area (Figure 4.69) indicates a more-mature sublitharenite to quartz arenite composition, again with an absence of feldspars similar to the Quweira Sandstone. These data are illustrative of the most mineralogically mature sandstone composition yet seen in the Al Ula area succession. Variable intraformational mud contents, affecting sandstone maturity, may be due to changes of the sedimentary source or alternatively an alteration in depositional energy, with no evidence of scouring of beds or deposition of mud clasts.

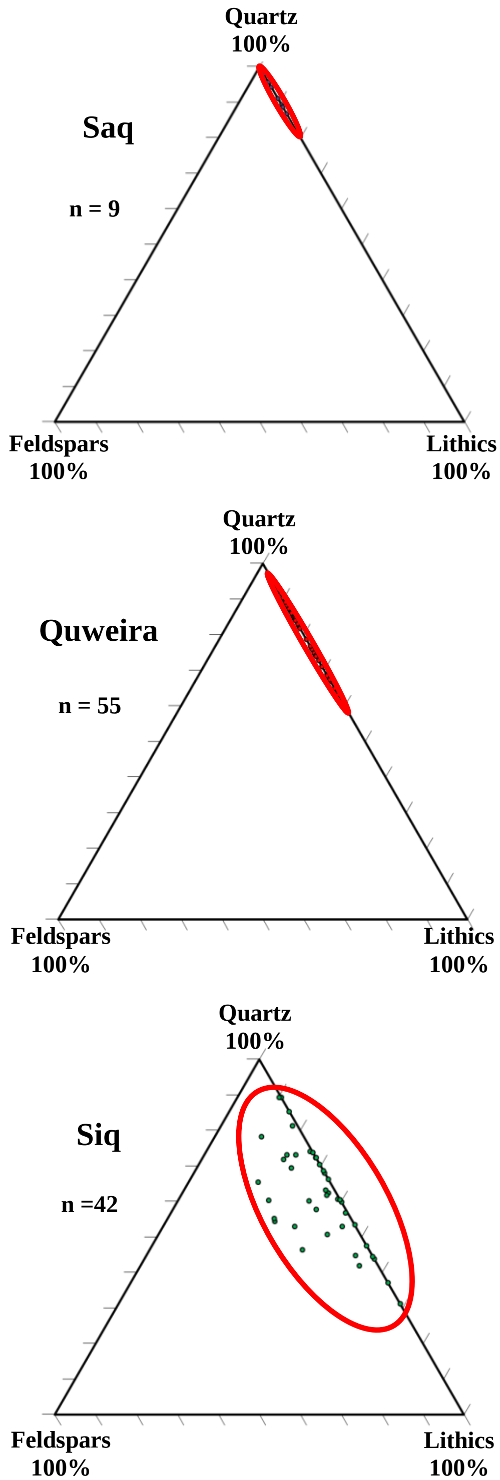


Figure 4.69: QFL (100%) ternary plot illustrating data collected from the Siq, Quweira and Saq Sandstones in the Al Ula area, from all measured sections and facies, highlighting the total number of samples included.

- **Petrographic Analysis of the Siq Sandstone in the Al Ula Area**

As previously discussed, the Siq Sandstone has been informally divided into the Lower, Middle and Upper units in this succession (see CHAPTER 1, P. 1). Therefore, three different ternary plots were constructed to clarify any petrographic differences among samples collected from these different sandstone units in the Al Ula area (Figure 4.70). The Lower Siq Sandstone petrographic analysis shows an overall feldspathic litharenite to litharenite sandstone composition. This dataset displays the most arkosic detrital mineralogy among all studied thin sections in this study. Thin sections studied in the Middle Siq Sandstone show a range of feldspathic litharenite, litharenite and sublitharenite sandstone composition. Petrographic data from the Upper Siq Sandstone, however, show complete loss of feldspars with composition ranging from litharenite to sublitharenite. These are the most mineralogically stable samples collected in the Siq Sandstone in the Al Ula area, and the loss of feldspars strongly suggests changes in the sedimentary source that commenced with deposition of this unit and appears to continue to be reflected (with increasing maturity) in the succeeding Quweira and Saq Sandstone successions (Figure 4.69)

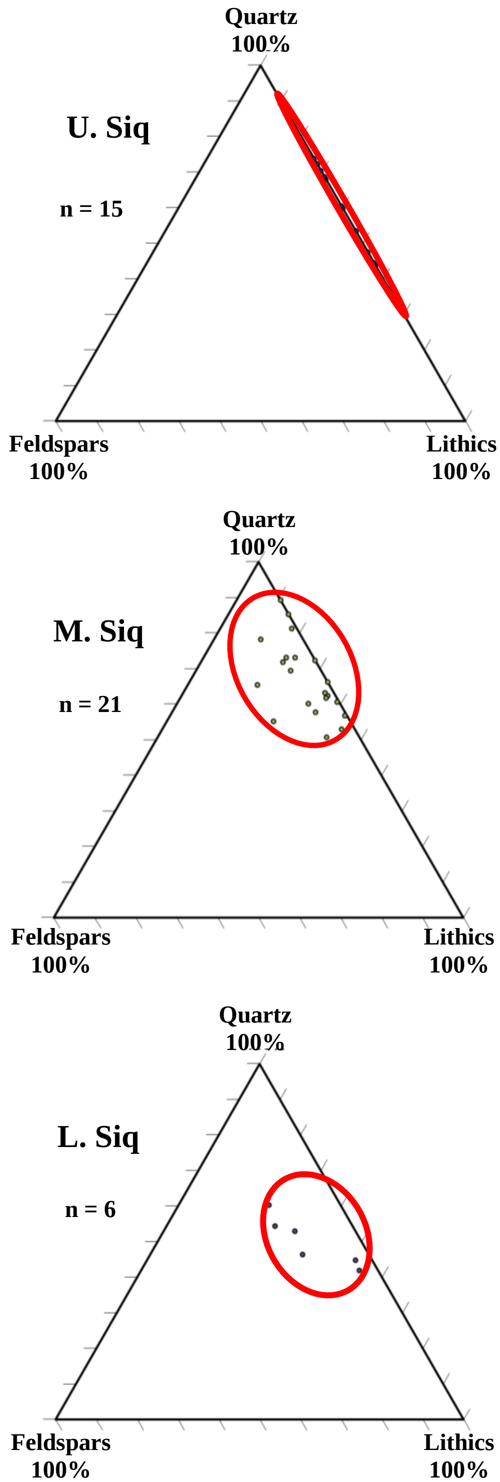


Figure 4.70: QFL (100%) ternary plot illustrating data collected from the Lower, Middle and Upper Siq Sandstones from all measured sections and facies, highlighting the total number of samples included.

4.3.2.2 Petrographic Analysis in the Tabuk Area

The point counted dataset from thin sections collected from the Tabuk area cover most parts of the Siq, Quweira and Saq Sandstones. The detrital compositions are plotted separately in QFL (100%) ternary plots (Figure 4.71). Petrographic analysis of the Siq Sandstone samples in this area suggests a composition variable between litharenite and quartz arenite, with trace amounts of feldspars. In comparison with petrographic analysis results from data collected from the Siq Sandstone units in the Al Ula area, the lack of feldspars is characteristic of the Upper Siq Sandstone (Figure 4.70). In addition to its stratigraphic position in the Tabuk area as conformably underlying the Quweira Sandstone, the Siq Sandstone exposure examined in Tabuk is also petrographically equivalent to the Upper Siq Sandstone in the Al Ula area. Therefore, the underlying two sandstone units of Lower and Middle Siq Sandstone, in addition to the Jibalah Group, may have been eroded away or possibly were never deposited in the Tabuk area. Petrographic analysis of data collected from both the Quweira and Saq Sandstones shows a gradually-increasing mineralogical maturity from sublitharenite to quartz arenite in each of the units (Figure 4.71). In comparison with the Quweira and Saq Sandstones in the Al Ula area, these two units in the Tabuk area show more mature sandstones (more quartz-rich).

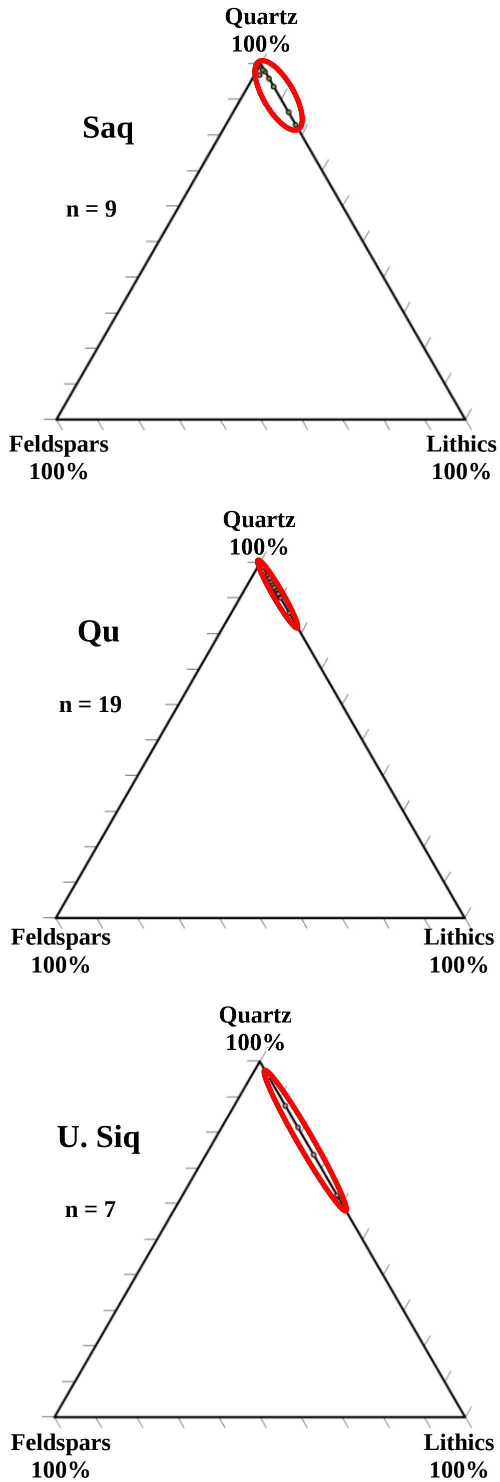


Figure 4.71: QFL (100%) ternary plot illustrating data collected from the Siq, Quweira and Saq Sandstones in the Tabuk area, from all measured sections and facies, highlighting the total number of samples included.

CHAPTER 5

DISCUSSION

Results utilizing all the collected data permit a thorough sedimentological interpretation of studied Early Paleozoic clastic successions in northwest Saudi Arabia through facies associations and distributions. When integrated with paleocurrent and petrographic analysis, this further enables differentiation between the different sandstone units in the context of lithostratigraphy in each study area, in addition to paleogeographic distinction between both of them. Datasets utilized include measured sections, which allowed for facies descriptions, associations and distributions, paleocurrent direction data and thin section descriptions and point count data.

5.1 Lithostratigraphic Studies in the Al Ula Area

A complete exposure of the Cambro-Ordovician clastic succession can be observed in the Al Ula area. This exposure includes the Siq, Quweira and Saq Sandstones. In this section, each of these sandstone units are examined separately. This will be followed by a summary of the complete succession in the area, establishing any lithostratigraphic similarities if any.

5.1.1 The Siq Sandstone in the Al Ula Area

Measured successions of the Siq Sandstone outcrops are found distributed among studied areas and measured sections. Occurring in the lower part of a composite section, the Siq Sandstone is divided into three sandstone units; the Lower, Middle and Upper Siq Sandstones. This division is apparent from the weathering profile of the outcrop in the area (Figure 5.1). The reddish-brown Siq Sandstone outcrops are characterized by a lower, cliff-forming outcrop, marked as Lower Siq Sandstone. This unit is conformably overlain by the Middle Siq Sandstone, which forms more gentle slopes that are commonly covered by scree in the area. The Upper Siq Sandstone is another cliff-forming succession that is conformably overlying the Middle Siq Sandstone. These three units will be considered independently to characterize differences between them.

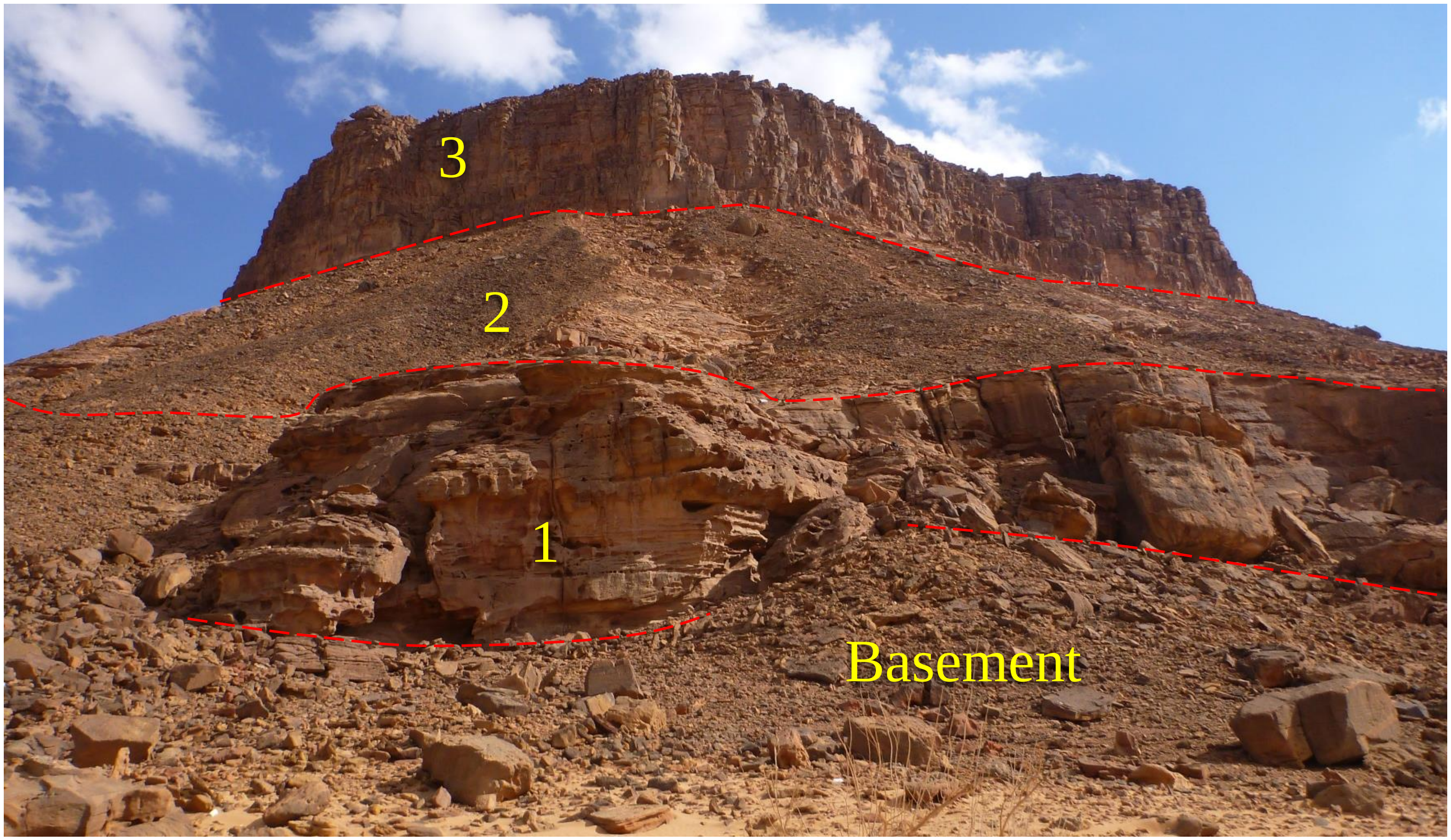


Figure 5.1: Illustration from section U101 in the Al Ula area, where the Siq Sandstone can be recognized as three separate units; 1) the Lower Siq; 2) the Middle Siq; and 3) the Upper Siq Sandstones; overlying the Precambrian basement. Note the part of Middle Siq Sandstone (2) where most of the succession is covered by scree.

5.1.1.1 The Lower Siq Sandstone in the Al Ula Area

This unit is limited to the Al Ula study area. Occurring above either a peneplaned unconformity with the basement or the Jibalah Group, the Lower Siq Sandstone in this study was included in measured section U101 (0.0-11.5 m – Appendix A) and is conformably overlain by deposits of the Middle Siq Sandstone deposits.

The limited exposure of this sandstone unit is dominated by tidally-influenced deposits (Facies 6 and 7), comprising high-energy tidally-dominated facies association (FA 4), with minor deformed beds (measured section U101 – Appendix A) (Figure 4.50). Paleocurrent analysis of this sandstone unit indicates a NW paleocurrent direction (Figure 4.55). Petrographic analysis in the Lower Siq Sandstone (Figure 4.70) show feldspathic litharenite to litharenite sandstones.

5.1.1.2 The Middle Siq Sandstone in the Al Ula Area

This unit, which is also limited to the Al Ula area, conformably overlies the Lower Siq Sandstone in measured section U101 and conformably underlie the Upper Siq Sandstone in measured section U102 (Appendix A). With a total measured footage of over 75 m, this unit is distinguished in the outcrop by a sloped profile that makes it susceptible to being covered by scree (Figure 1.3, Figure 5.1 and Figure 5.2). This hindered sedimentological section measurement, but the acquired data is nonetheless considered representative of the depositional characteristics of this sandstone unit.

The basal contact of this unit shows a rejuvenation of braided-fluvial deposition (measured section U101 – Appendix A), marked by the occurrence of cross-bedded sandstones (Facies 3, 4 and 5), in fluvial-dominated I facies association (FA 1). This is followed by deposits of mixed fluvial-tidal facies association (FA 3), indicative of an estuarine setting (measured section U101). Followed by a drop in fluvial deposition, tidal influence becomes more pronounced by the occurrence of low-energy tidally-dominated facies association (FA 5) deposits throughout the remainder of the Middle Siq Sandstone in the Al Ula area (measured section U101), displaying sporadic occurrences of mixed fluvial-tidal and high-energy tidally-dominated facies associations (FA 3 and 4) deposits (Facies 3 through 8). Facies Associations 3 and 5 are limited to the Middle Siq Sandstone in both study areas.

Sitting above the top of the logged part of measured section U101, the remainder of the outcrop, mostly covered by fallen rocks, was examined (but not necessarily measured) to determine if there were any changes in depositional facies patterns or trends (see note in measured section U101 – Appendix A). Silty to argillaceous, finer-grained (flat-laminated) beds (Facies 9 and 10) appear in progressively-thicker bedding with the display of isolated fluvial-tidal facies deposits that decrease in frequency higher in the section. These thick accumulations of fine-grained facies possibly mark the end of a very long transportation sequence that persisted over a long period of time. The facies that mark the highest parts of the Middle Siq Sandstone in measured section U102 show similar relationships.

Depositional facies of the Middle Siq Sandstone (Figure 4.50) show wide-spread distribution due to varying facies associations observed (FA 1 through 5). Paleocurrent direction data collected in this sandstone unit indicate a NNW paleocurrent direction

(Figure 4.55). Petrographic analysis of samples from this unit (Figure 4.70) shows a feldspathic litharenite to litharenite and sublitharenite sandstones.

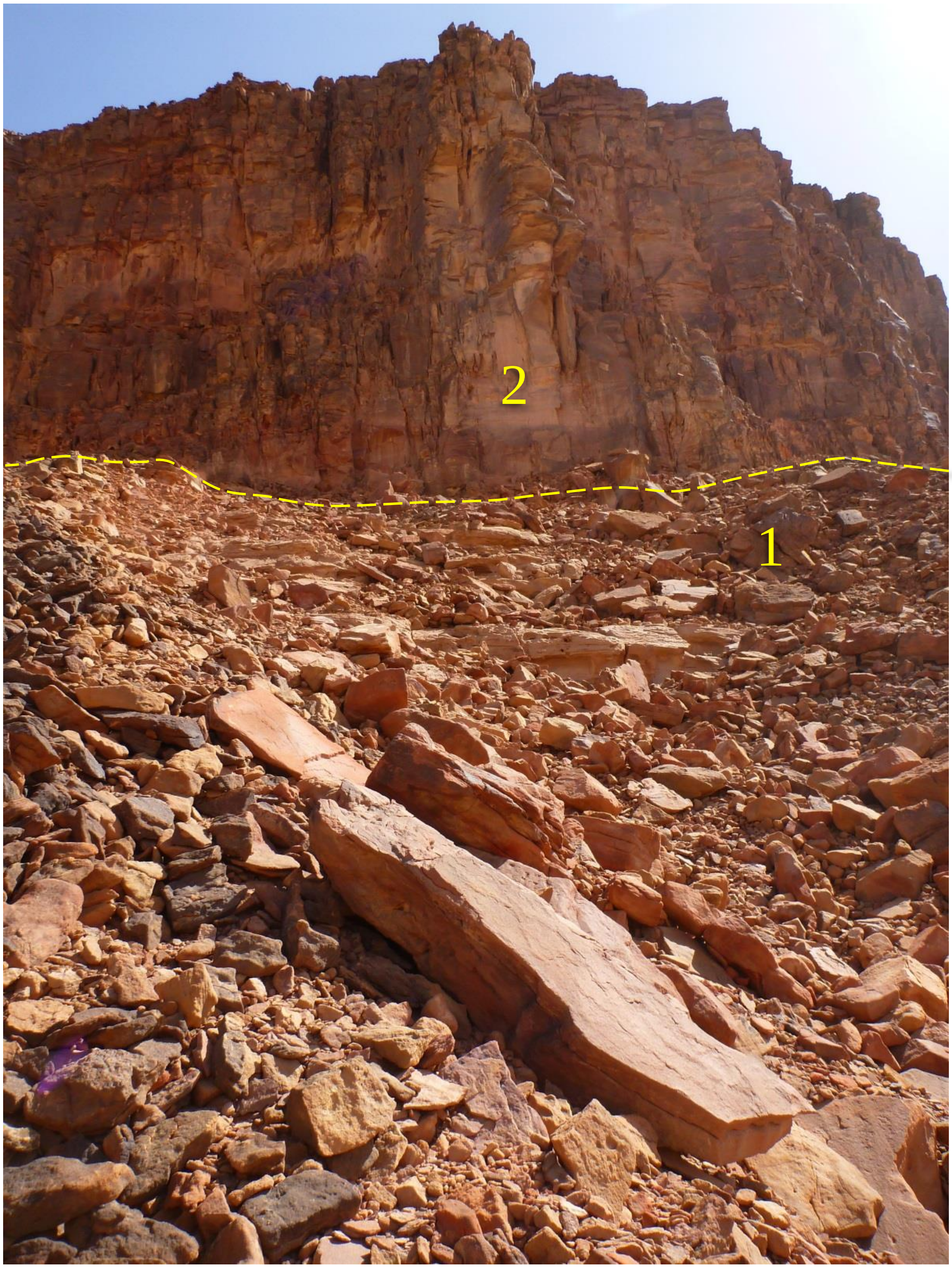


Figure 5.2: Top of measured section U101 (Appendix A), where most of the section becomes covered by scree. This prevented complete description of this unit in this locality. Note the estimated boundary between the Middle and the Upper Siq Sandstone in the sections was investigated by not logged in the measured section.

5.1.1.3 The Upper Siq Sandstone in the Al Ula Area

This sandstone unit is conformably overlying the Middle Siq Sandstone and conformably underlying the Quweira Sandstone in study areas U1 and U3 (Appendix A) (Figure 1.3, Figure 5.1 and Figure 5.2).

Above the basal contact of this sandstone unit (measured section U102 – Appendix A) there is a pronounced rejuvenation of fluvial-dominated deposition (FA 1) (Figure 4.50), with a presence of trough cross-bedded sandstones (Facies 3 and 4) persisting throughout the unit (Figure 5.3). Fluvial dominated (II) facies association (FA 2) is observed less commonly. Showing greater concentrations of pebble-sized mud clasts in addition to quartz pebbles in different sizes and shapes, these are indicative of recurring deep-scouring and reworking of finer-grained sediments of the tidally-influenced Middle Siq Sandstone in migrating braided-fluvial channel depositional setting (measured sections U102 and U301). Lower-energy fine-grained deposits (Facies 9 and 10) are found locally and are silty, argillaceous and micaceous in places. Local lag deposits show high concentrations of pebble-size mud clasts (Figure 5.4) in addition to desiccation surfaces marked by mud cracks.

Facies distribution in the Upper Siq Sandstone in the Al Ula area (Figure 4.50) show complete dominance of braided-fluvial deposits (Facies 3, 4 and 5), in addition to tidally-influenced deposits (Facies 6 and 7) in mainly fluvial-dominated (I) and (II) facies associations (FA 1 and 2) sequences. Paleocurrent analysis in this sandstone unit shows a NE paleocurrent direction (Figure 4.55). Petrographic analysis of the Upper Siq Sandstone (Figure 4.70) indicates a significant difference from the older Lower and

Middle Siq Sandstones, with an almost total absence of feldspars, and a sandstone composition ranging from litharenite and sublitharenite sandstones.

Figure 5.3: Contact between 1) the Middle Siq; and 2) the Upper Siq Sandstones in the Al Ula area (measured section U102 – Appendix A).

Figure 5.4: Lag showing high concentrations of mud clasts in parts of the Upper Siq Sandstone succession. Mud pebbles occur in different shapes, but mostly well-rounded (measured section U301 at 25.0 m – Appendix A).

5.1.1.4 The Siq Sandstone in the Al Ula Area (Summary)

From the foregoing discussion about the three sandstone units of the Siq (Figure 1.3), the evolution of this sandstone in the Al Ula area can be summarized as follows (Figure 5.5):

1. The limited exposure of the Lower Siq Sandstone shows dominance of high-energy tidal-influenced deposition with no input of fluvial sedimentation.
2. The Middle Siq Sandstone shows high-energy braided-fluvial channel deposition at the base, followed by variable tidally-influenced facies associations in fining-upward sequences, strongly suggestive of an estuarine setting. The top of this sandstone unit shows evidence of very-low depositional energy, possibly indicative of an end of a major depositional event.
3. Above the base of the Upper Siq Sandstone, there is a clear rejuvenation of high-energy braided-fluvial in-channel deposition with little evidence of tidal-influence. This is reflected in the difference in the facies distribution in this sandstone in comparison to the underlying sandstones of the Lower and Middle Siq. In addition to the previous observation, the Upper Siq Sandstone displays significant shifts in both paleocurrent direction (from NW to NE), and petrographic composition, where these sandstones become remarkably feldspar-free, in comparison with the underlying Lower and Middle Siq Sandstones. This strongly suggests that the base of the Upper Siq Sandstone marks a new lithostratigraphic unit. Furthermore, this shift in properties appears also to be indicative of a major change in sedimentary source and possibly even tectonic setting during deposition.

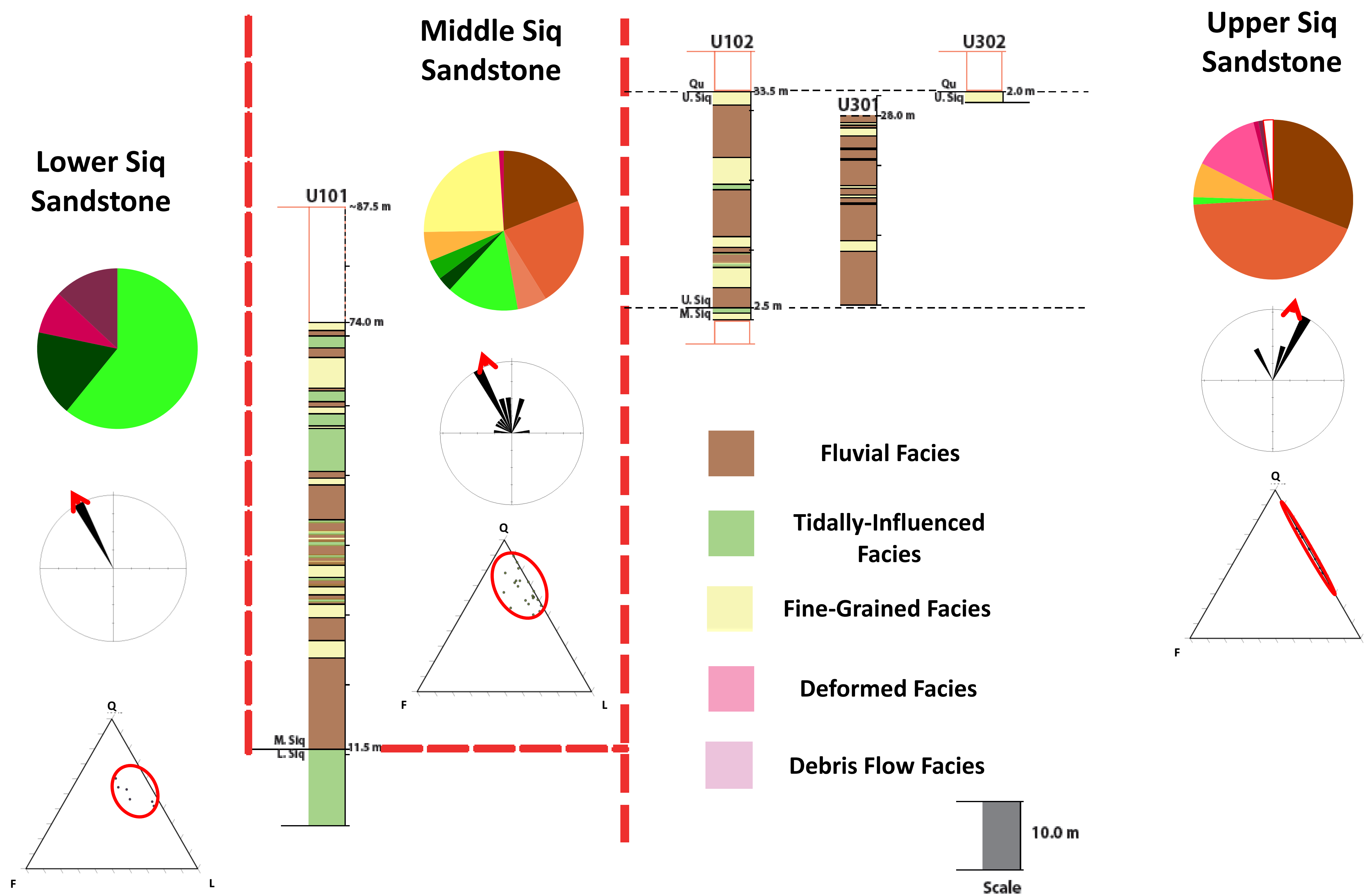


Figure 5.5: Summary display of datasets collected from the Siq Sandstone units in the Al Ula area, including measured sections displaying facies associations, in addition to QFL (100%) ternary plots, paleocurrent direction rose diagrams and facies distribution pie charts for each of the Siq Sandstone units.

5.1.2 The Quweira Sandstone in the Al Ula Area

This sandstone unit is found to account for the majority of the studied footage in the Al Ula area (more than 50% of total measured footage throughout the study). Examined in four study areas (U1 through U4), the Quweira Sandstone conformably overlies the Upper Siq Sandstone. The upper contact with the Saq Sandstone could not be characterized in the Al Ula area. Due to the large footage and descriptions collected in this sandstone unit, it is possible to characterize the Quweira Sandstone in the Al Ula area in different parts; lower (basal), middle and upper. This will allow establishing more thorough descriptions and interpretations of any sedimentological changes throughout this unit, which might enable lithostratigraphic distinctions, if any.

5.1.2.1 The Lower Part of the Quweira Sandstone in the Al Ula Area

The lower contact of the Quweira Sandstone, observed in measured sections U102 and U302 (Appendix A) (Figure 5.6), is characterized by thick succession of fluvial-dominated facies associations (FA 1 and 2), showing 20-40 cm thick conglomeratic trough cross-bedded sandstone sets (Facies 2) at bases of cycles (Figure 5.7). This high-energy deposition is suggestive of a major tectonic reactivation that allows the generation of such pebble-size particles, similar to the underlying Upper Siq Sandstone. Type-II fluvial-dominated facies association (FA 2), only observed in measured section U102, possibly indicates laterally-variable tidal-influence (Figure 4.51 for facies distribution; area U1).

Pebbles observed in these deposits mostly include rounded quartz with less abundant feldspars, mud clasts and granitic fragments. Mud clasts most likely originated locally, and feldspars and granitic fragments more likely indicate extrabasinal sourcing.

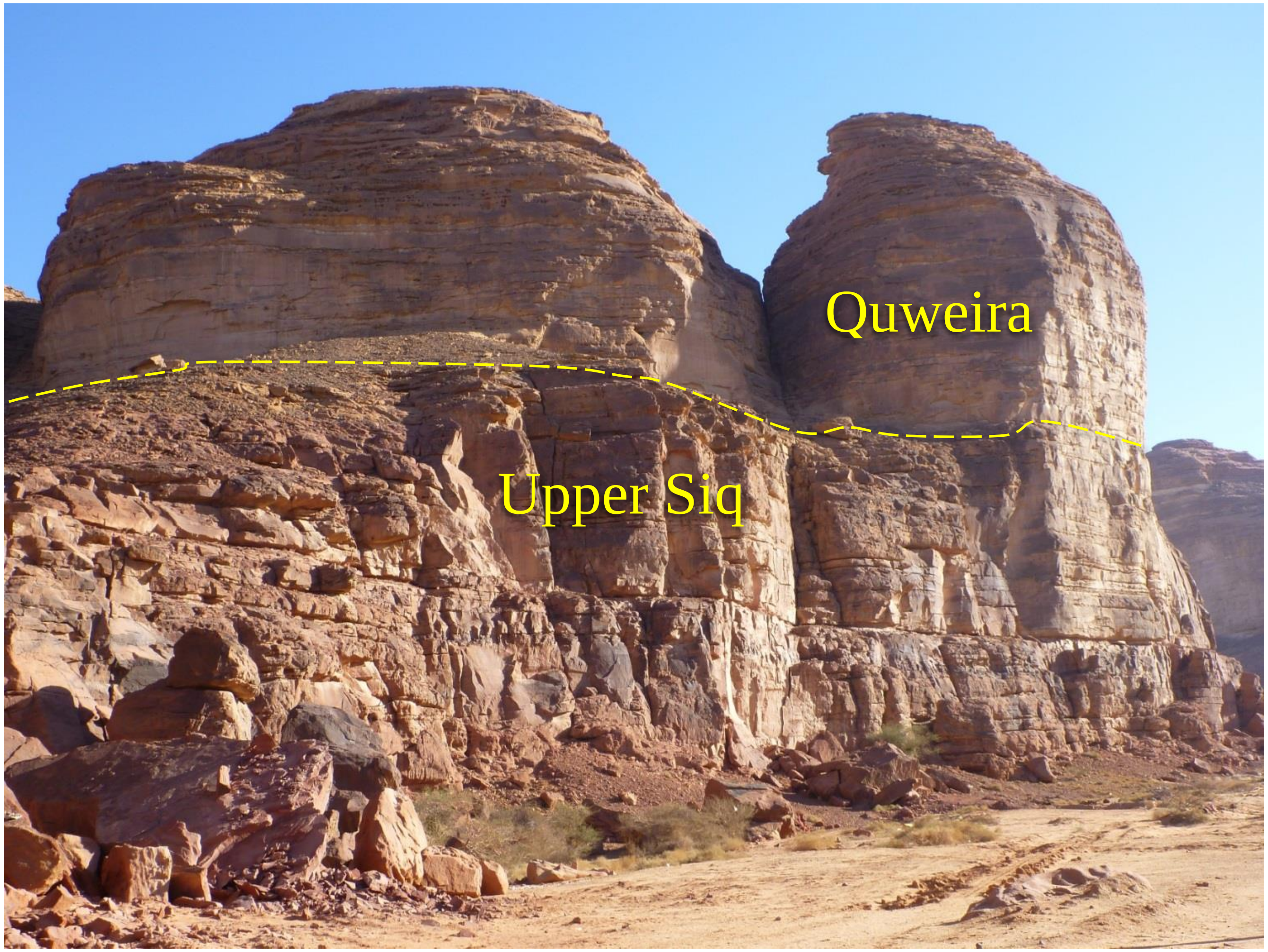


Figure 5.6: Conformable contact between the Upper Siq and the Quweira Sandstones in area U3 in the Al Ula area (Appendix A).

Figure 5.7: Conglomeratic trough cross-bedded sandstone sets (Facies 2) (arrow) mark the lower contact of the Quweira Sandstone in the Al Ula area (measured section U102 at ~ 37.0 m – Appendix A).

5.1.2.2 The Middle Part of the Quweira Sandstone in the Al Ula Area

The middle part of Quweira Sandstone (represented in measured sections U103, U302, U303 and U304 – Appendix A) shows sandstone succession of fluvial deposits (Facies 3 through 5), dominated by in-channel deposition in fluvial dominated facies associations (FA 1 and 2). Pebbles are mostly well-rounded quartz with minor to rare display of mud clasts. This high-energy fluvial depositional setting, with minor tidal-influence is consistent in this part of the sandstone unit in fining-upward sequences. Minor deformed beds (Facies 11 and 12) are also observed in this part of the succession.

Tidal-influence is locally predominant (measured sections in the Mada'in Saleh area; U201 and U202; which found further north to area U3 – Appendix A) with the presence of fining-upward, fluvial-dominated (II) and high-energy tidally-dominated facies association sequences (FA 2 and 4), indicative of possibly lateral variations in the depositional setting relative to the general fluvio-estuarine setting. Bioturbation observed in parts of these measured sections (and traceable also at the same stratigraphic position elsewhere in area U2 within Mada'in Saleh) also supports such lateral variations (Figure 5.8 and Figure 5.9). These variations are also reflected in the facies distribution in this part of the Quweira Sandstone (Figure 4.51 for facies distribution; area U2).

Figure 5.8: Flat-laminated to massive sandstone bed (Facies 10) shows evidence of bioturbation (section found in Mada’in Saleh area; U2).

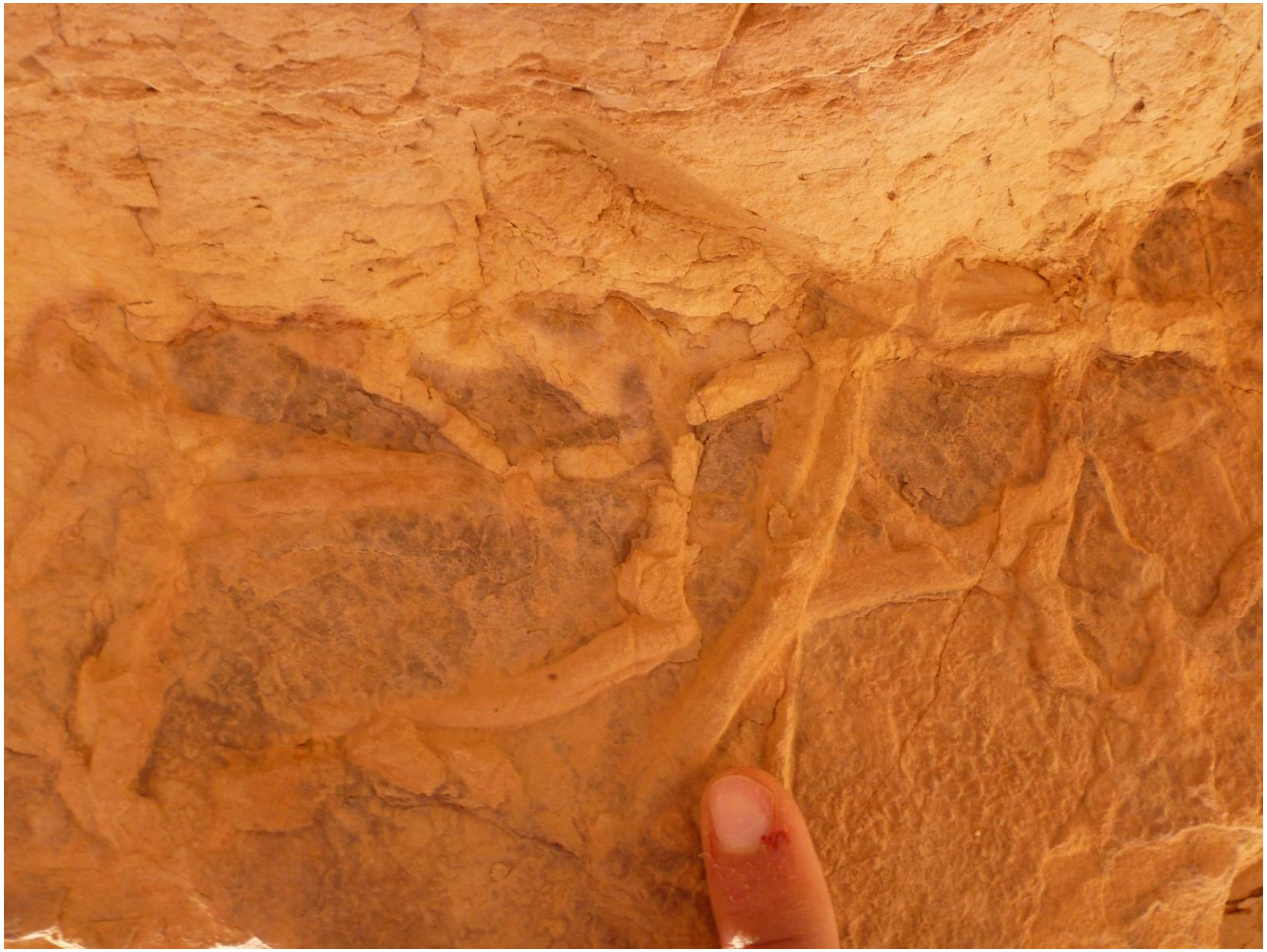


Figure 5.9: Facies 10 bedding observed in previous figure, showing horizontal trace fossils in situ on the underside of bedding (Mada'in Saleh study area; U2).

5.1.2.3 The Upper Part of the Quweira Sandstone in the Al Ula Area

The upper part of the Quweira Sandstone in the Al Ula area (observed in parts of measured sections U305 and U401 – Appendix A) displays a dominance of fluvial-dominated facies association deposition (FA 1) with minor and local tidally-influenced fluvial-dominated facies association deposition (FA 2) in fining-upward successions. Deformed beds have variable occurrence in this part of the succession (Facies 11 and 12). Facies distribution in this part of the Quweira Sandstone continues to show dominance of fluvial facies, with minor presence of tidally-influenced, low-energy and deformed facies (Figure 4.51).

In measured sections U305 (between 12.0 and 21.5 m) and U401 (between 25.0 and 30.5 m) (Appendix A) around the middle of this higher part of the Quweira Sandstone in the Al Ula area, there are three major, very high-energy depositional events. These events are characterized by a number of sets of sandy cross-bedded conglomerate (Facies 1) that display a very high concentration of pebbles in a very coarse sandy matrix. These beds are considered to be fluvial and it is possible they relate to tectonic stimuli in the basin at this time. Clast types range between quartz (angular to well-rounded and fragmented), intraformational mud clasts (well-rounded and rip-ups), subordinate feldspars and granitic rock fragments. These beds are often found associated with deformed sandstone facies above and below.

5.1.2.4 The Quweira Sandstone in the Al Ula Area (Summary)

Observations of sequences in the Quweira Sandstone in the Al Ula area can be summarized in the following points (Figure 5.10):

1. Fining-upward sequences in the Quweira Sandstone are dominated by high-energy fluvial deposition with variable tidal-influence in the overall more-fluvial setting (FA 1 and 2). These conclusions can be observed in the more-fluvial facies distribution of this sandstone unit between the different studied areas (U1 through U4) in the Al Ula area. (Figure 4.49 and Figure 4.51).
2. These sequences show evidence of significant high-energy fluvial deposition, marked by the presence of sandy cross-bedded conglomerate and conglomeratic trough cross-bedded sandstone deposits (Facies 1 and 2), which are only observed in this unit throughout the study in both locations.
3. Tidal-influence varies laterally, with observations of higher-energy tidal-dominant deposition, locally topped by bioturbated sandstones, observed in parts of the succession in area U2 in the Mada'in Saleh area (Figure 4.51).
4. These observations are indicative of long-lived, migrating in-channel braided-fluvial depositional setting and less-commonly occurring high-energy tidal-influenced deposition within an estuary.
5. Paleocurrent data collected from the Quweira Sandstone in the Al Ula area show a dominant flow direction towards the NNE (Figure 4.54).

6. Petrographic analysis of thin sections of samples collected in this sandstone unit show an increasingly-maturing sandstone composition, progressing from litharenite to quartz arenite (Figure 4.69).

7. Observations from facies distribution, facies associations, paleocurrent and petrographic analysis differ in the Quweira Sandstone from the Lower and Middle Siq Sandstones. However, these observations show consistency with data collected from the Upper Siq Sandstone. Thus, it is believed that the base of the Upper Siq Sandstone marks the base of a major lithostratigraphic unit that includes the Quweira Sandstone in the Al Ula area. This unit shows evidence of a more persistent fluvial system, locally showing more conglomeratic deposits, with less-commonly tidal input among these deposits.

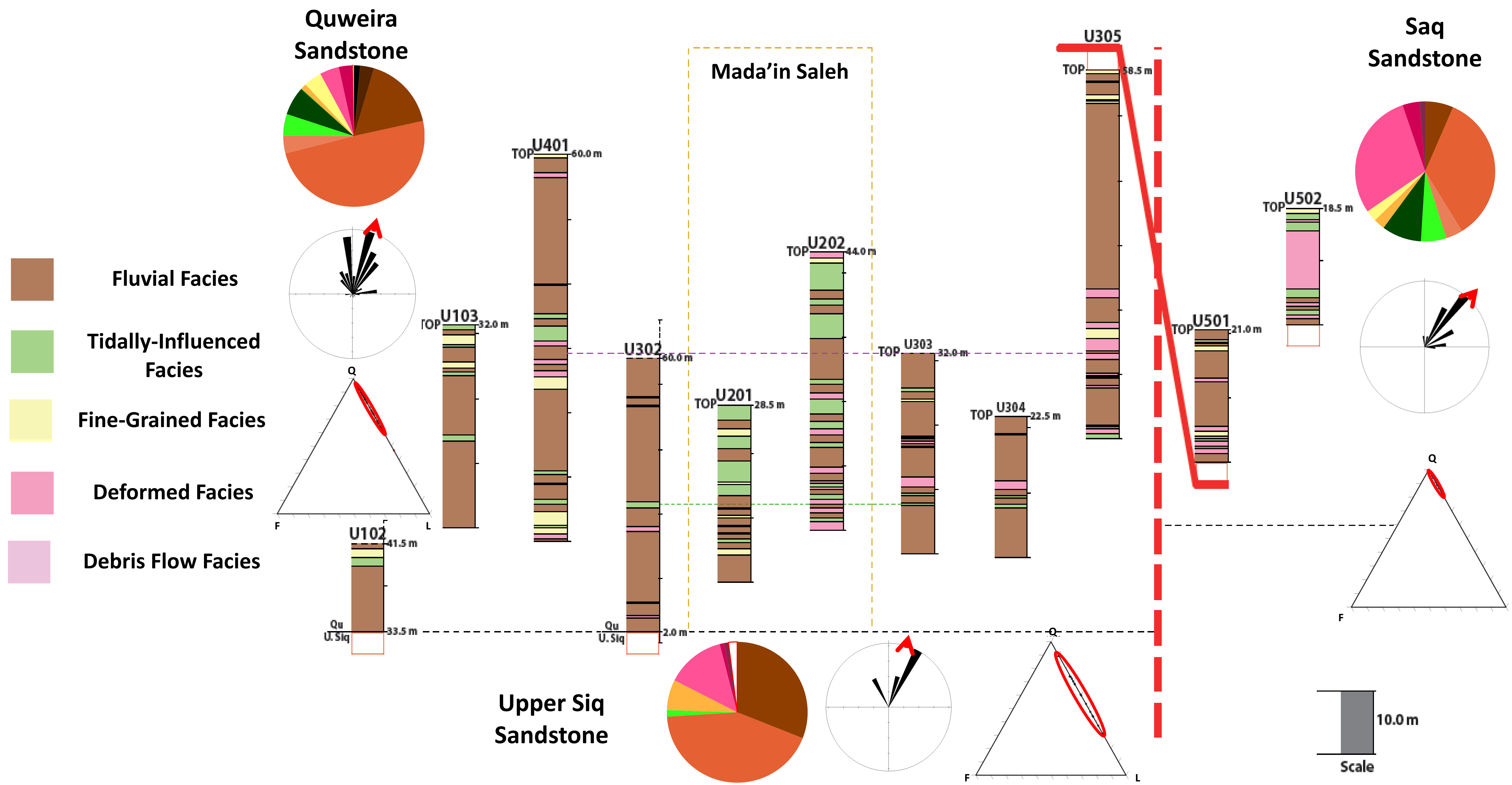


Figure 5.10: Summary display of datasets collected from the Upper Siq, Quweira and Saq Sandstone units in the Al Ula area, including measured sections displaying facies associations, in addition to facies distribution pie charts, paleocurrent direction rose diagrams and QFL (100%) ternary plots for each of these units.

5.1.3 The Saq Sandstone in the Al Ula Area

Limited sandstone sequences cropping out further north to the main study area near Al Ula, including measured sections in area U5 (Appendix A) (Figure 3.3), are recognized as the Saq Sandstone based on the Shaghab quadrangle report and map (Grainger & Hanif, 1989). No determined contact was possible to observe with the underlying Quweira Sandstone due to limited exposure. These outcrops were logged and are included in this study for completeness.

Saq Sandstone measured successions show no changes in depositional sequences, showing fluvial-dominated facies associations (FA 1 and 2), as observed in measured sections U501 and U502 (Appendix A). However, these described sequences show new characteristics not observed in the underlying units. Tidally-influenced deposits near tops of sequences of Facies Association 2 show sigmoidal cross-bedded sandstone beds (Facies 6) that show clear bundled foresets, which probably reflect a degree of marine flooding in an interpreted fluvio-estuarine environment. Succession of the Saq Sandstone in the Al Ula area displays the predominant effect of deformation, resulting in sequences of deformed facies association (FA 6), rarely-observed elsewhere in this succession (as observed in measured section U502 between 1.0 and 15.0 m). These deformed sequences are possibly indicative of pervasive deformation of individual sets due to rapid sedimentation rate that in turn could be a reflection of a significant change in climate (sustained rainfall) and possibly an indication of ongoing seismicity within the basin. Local fine-grained tops (Facies 9 and 10) often show white to deep-purple sandstones, displaying *Cruziana* trace fossils. These bioturbated tops are very distinctive and they are commonly used to mark the Risha member of the Saq Sandstone in central Arabia (Vaslet, 1987) and in this locality (Grainger & Hanif, 1989).

Following section measurements in this study, a more general reconnaissance of outcrops further to the north of area U5 suggested that the cycles measured and described above diminish in size (thickness) with the loss of the fluvial component and the proportional gain of bioturbated- *Cruziana* beds. Ultimately, these are replaced by sandstones that show dense concentration of *Skolithos* burrows, possibly indicating a maximum transgression, recognized in central Arabia to mark the Sajir member of the Saq Sandstone, overlying the Risha member (Vaslet, 1987).

In this study, lithostratigraphic descriptions of the Saq Sandstone in the Al Ula study area show consistency with the underlying Upper Siq and Quweira Sandstones (Figure 5.10). Facies distribution show dominance of fluvial depositional facies and facies associations, with a noticeable increase of deformed facies, in addition to tidally-influenced and fine-grained facies, as part of type II fluvial-dominated facies association (FA 2) (Figure 4.49). Paleocurrent direction analysis show results similar to the underlying Quweira Sandstone (Figure 4.54). Petrographic analysis of this unit continues to show more sandstones of sublitharenite to quartz arenite composition (Figure 4.69) with no feldspars.

5.1.4 Lithostratigraphic Studies in the Al Ula Area (Summary)

Conclusions regarding the Cambro-Ordovician succession in the Al Ula area can be summarized in the following points:

1. The sandstone succession formally comprises three sandstone units, the Siq, Quweira and the Saq Sandstone, which unconformably overlie the Precambrian basement and the Jibalah Group. This succession includes two lithostratigraphic units, based on facies distribution, facies associations, paleocurrent and petrographic analysis
2. The first lithostratigraphic unit, comprising the Lower and Middle Siq Sandstones show evidence of braided in-channel fluvial-dominant deposition (FA 1), and variable high- and low-energy tidal-influenced deposition (FA 2 through FA 5). This unit shows a progressive drop in both fluvial and tidal energies in fining-upward sequences within an estuary. These sandstone sequences show relatively consistent paleocurrent direction towards the NW, with a relatively more-feldspathic sandstone composition (Figure 5.5).
3. The second overlying lithostratigraphic unit, including the Upper Siq, Quweira and Saq Sandstone is characterized by high-energy braided-fluvial deposition (FA 1). Deposited sequences mainly show in-channel, sinuous-crested trough cross-bedded sandstones that include more conglomeratic deposits (Facies 1 and 2). Tidal influence in this fluvio-estuarine setting shows evidence of high-energy deposition in fluvial-dominated and high-energy tidally-dominated facies associations (FA 2 and 4). These sequences also show evidence of lateral variability. Deformation of beds is found variable throughout this lithostratigraphic unit, mostly in isolated deformed beds (Facies 11, 12 and 13) or deformed facies association (FA 6) higher in the unit. Deformation is principally considered evidence of rapid sedimentation rate in fluvial deposition settings.

Facies distribution in this lithostratigraphic unit shows dominance of fluvial facies and facies associations, a shift in paleocurrent flow direction from NW in underlying beds to the NE, and feldspar-free sandstones (Figure 5.10).

4. The major cycle that commences at the base of the Upper Siq Sandstone and persists throughout the succession into the rocks identified as the Saq Sandstone calls into question the definitions of stratigraphic boundaries of this part of the Early Paleozoic.

5. Implications of changes in the tectonic setting in this part of the Early Paleozoic deposition are suggested between the different lithostratigraphic units identified and described in this study. These implications are strongly suggested by the determined changes in paleocurrent direction and sandstone petrographic properties.

5.2 Lithostratigraphic Studies in the Tabuk Area

Parts of the Cambro-Ordovician clastic succession are observed in the Tabuk area of this study (Figure 3.4). Selected outcrops were considered in this area based on their stratigraphic position in an older-to-younger line of section (T1). This area was included in this study to investigate and characterize paleogeographic variations and discontinuities of the Cambro-Ordovician clastic succession in northwest Saudi Arabia. Studied sections include parts of the Siq Sandstone, the Quweira and Saq Sandstones, unconformably overlying the Precambrian basement at a peneplaned surface (Figure 1.4). These different sandstone units will be discussed separately in this chapter in the context of their lithostratigraphy.

5.2.1 The Siq Sandstone in the Tabuk Area

The Siq Sandstone is observed in the Ash' Shiq area near Tabuk (measured section T101 – Appendix A). These reddish-brown rocks are found at an unconformable peneplaned contact with the basement (Figure 1.4), marking the earliest sedimentary deposition of the Cambro-Ordovician. It is conformably overlain by the Quweira Sandstone. The Siq Sandstone was examined in one measured section (T101), directly above the Ash' Shiq exposure in the area, cited as the As' Siq section[1] in Bramkamp et al. (1963) where the type locality of this sandstone unit is referenced.

The Siq Sandstone (observed in measured section T101 between 0.0 and 16.5 m – Appendix A) shows mixed fluvial-tidal deposition. Fining-upward sequences display fluvial-dominated and high-energy tidally-dominated facies associations (FA 1, 2 and 4), showing progressive increase in tidal influence and are characterized by fine-grained deposits (Facies 9 and 10) near tops of cycles. Near the top of this sandstone unit, apparent by a general change in topography, a fine-grained sandstone bed shows concentrations of *Skolithos* trace fossils (measured section T101 at 15.0 m) (Figure 4.27). The tidal-dominant depositional setting topped by these bioturbated sandstones is suggestive of a drowned estuarine depositional setting. The bioturbated sandstone bed is directly overlain by fine-grained sandstone beds (Facies 10) that display an abundance of syneresis and desiccation mud cracks (Figure 4.28 and Figure 4.29). This is also suggestive of a riverine/marine interaction and is considered a marker of the upper

[1] The sandstone unit name: Siq Sandstone refers to no near-by locality and has no proper meaning in Arabic. Being the section referenced by Bramkamp et al. (1963), The author believes that the name: As' Siq was meant to say: Ash' Shiq, in reference to the canyon. The original name: Ash' Shiq might have been lost in translation from Arabic to English or English to English word articulation.

contact of this sandstone unit. The Siq Sandstone sequences in the Tabuk area also show deformed sandstone beds (Facies 11 and 12).

The Siq Sandstone in the Tabuk area shows a variable distribution between fluvial, high- and low-energy tidally-influenced and deformed facies in limited fluvial to more tidally-dominated facies associations (Figure 4.52). The wide spread of flow direction readings in this sandstone is possibly related to the effect of tidal deposition. The vector mean value of paleocurrent direction measurements in this sandstone unit indicates a NW flow direction (Figure 4.56). Thin section analysis shows litharenite to quartz arenite sandstone compositions with traces of feldspars, which could have generated from the underlying basement (Figure 4.71). Observations from paleocurrent and petrographic analysis of the Siq Sandstone in the Tabuk area, in addition to its stratigraphic position directly below the Quweira Sandstone, appears to confirm its equivalency to only the Upper Siq Sandstone in the Al Ula area. A summary of these observations can be seen in Figure 5.11.

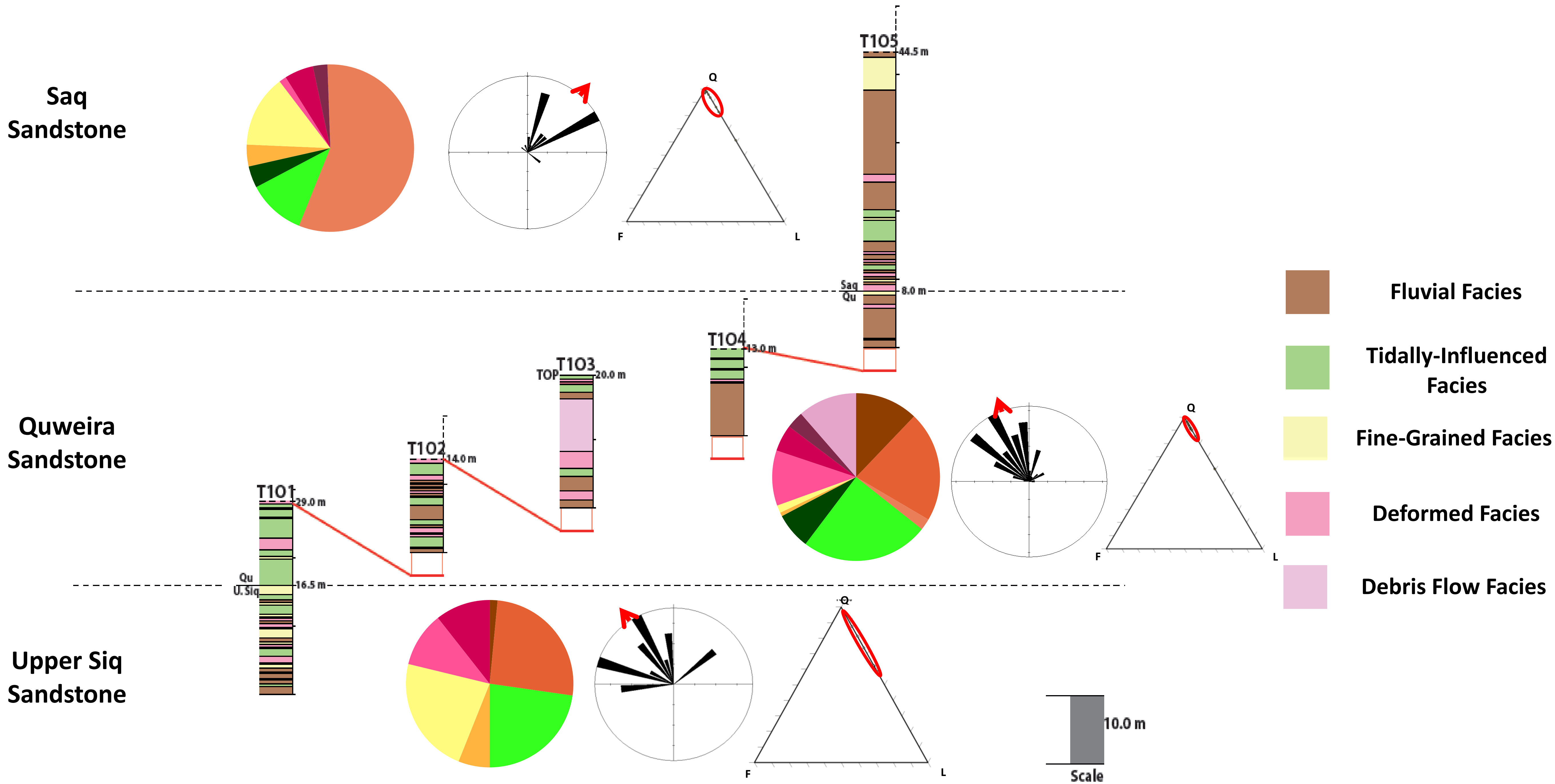


Figure 5.11: Summary display of datasets collected from the Upper Siq, Quweira and Saq Sandstone units in the Tabuk area, including measured sections displaying facies associations, in addition to facies distribution pie charts, paleocurrent direction rose diagrams and QFL (100%) ternary plots for each of these units.

5.2.2 The Quweira Sandstone in the Tabuk Area

This sandstone unit is observed in outcrops throughout the Tabuk area. Examined in all measured sections (T101 through T105 – Appendix A), the Quweira Sandstone conformably overlies the (Upper) Siq Sandstone. Its upper contact with the Saq Sandstone is also conformable (measured section T105).

The Quweira Sandstone sequences show limited fluvial-dominated (I) facies association deposits (FA 1) (measured section T104 – Appendix A). The succession is dominated by tidally-influenced deposits, including fluvial-dominated (II) and high-energy tidally-dominated facies associations (FA 2 and 4) (measured sections T101, T102 and T104), showing characters of tidal-deposition such as large bundled-foresets and double-clay draped foresets in cross-bedded sandstone sets (Facies 6) (Figure 4.14 and Figure 4.15). The widespread indications of tidal bar deposition in these sequences are suggestive of deposition within a drowned estuary. Deformation of sandstone beds is prevalent throughout the Quweira Sandstone in the Tabuk area (Facies 11, 12 and 13), suggestive of rapid sedimentation.

Measured section T103 (Appendix A) shows deposition of three very poorly-sorted paraconglomerate beds (Facies 14) overlying variably deformed sandstone beds (Facies 11 and 13). These deposits have been interpreted to derive from debris flow deposition, possibly as a result of a catastrophic event (FA 7). Deformation of underlying sandstones resulted from either non-confined pressures created by the deposition of the debris flow or as a result of the same catastrophic event. This facies association observed within the Quweira Sandstone in the Tabuk area strongly suggests a tectonic influence in the deposition of this sandstone unit.

Facies distribution observed in the Quweira Sandstone in the Tabuk area (Figure 4.52) compare strongly with the underlying (Upper) Siq Sandstone, showing fluvial and slightly more tidally-influenced facies and facies associations deposits. A large portion of the facies distribution of the Quweira Sandstone in the Tabuk study area is dedicated to the debris-flow event (~20% of total). Observations noted from both paleocurrent and petrographic analysis (Figure 4.56 and Figure 4.71) also show similarities with the (Upper) Siq Sandstone. Paleocurrent analysis demonstrates a reduced spread in river flow directions in comparison with the underlying Upper Siq Sandstone, mainly towards the NW. Petrographic analysis shows a more-mature, quartz rich sublitharenite to quartz arenite sandstone compositions in comparison with the underlying Upper Siq Sandstone with no feldspars (Figure 5.11). Thus, the lithostratigraphic characteristics of the Quweira Sandstone show very strong comparison with the underlying sandstone unit, hitherto referenced as the Siq Sandstone.

5.2.3 The Saq Sandstone in the Tabuk Area

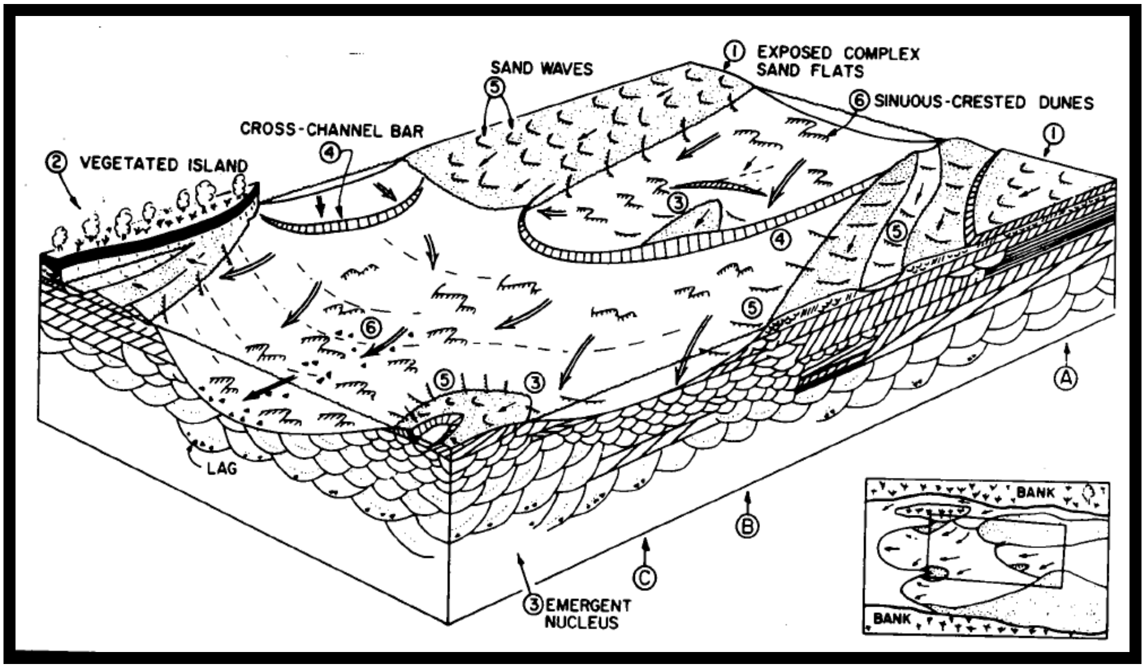
Limited footage of the Saq Sandstone has been observed and described in the Tabuk area. Above a conformable contact with the Quweira Sandstone (measured section T105 – Appendix A), observations in this sandstone unit demonstrate a change in depositional facies and therefore depositional setting from the underlying sandstones in this study area.

Sequences of the Saq Sandstone in the Tabuk area are dominated by fluvial-dominated type I, and less-commonly type II, facies associations (FA 1 and 2). These fluvial-dominated sequences differ from other braided-fluvial sandstone units studied in both locations by being dominated by planar-tabular cross-bedded sandstone (Facies 5), indicative of sand-flat deposition in a braided-fluvial setting, lacking in-channel deposits of sinuous-crested trough cross-bedded sets (Figure 4.10). Observations of the different braided-fluvial depositional settings in this study matches interpretations in previous work in the Saskatchewan River by Cant and Walker (1976), in the Devonian Battery Point Formation 3-D and sequence models, where variations between in-channel and sand flat deposition are interpreted as a reflection of channel migration and water depth variations (Figure 5.12). Fining-upward sequences of both facies associations observed show evidence of bioturbation at tops of cycles, characterized by the presence of *Cruziana*[1] and *Skolithos* (Figure 5.13) trace fossils (measured section T105 – Appendix A). Deformed sandstone facies (11 and 12) are found at various places within the Saq Sandstone in the Tabuk area.

Depositional facies of the Saq Sandstone are dominated by planar-tabular cross-bedded deposits as discussed (Facies 5), in addition to limited tidally-influenced deposits of both high- and low energy (Facies 6, 7, 9 and 10) (Figure 4.52). In comparison to underlying sandstone units, The Saq Sandstone in the Tabuk area illustrates evidence of a rejuvenation of fluvial deposition at the base. Paleocurrent analysis shows a shift in paleocurrent direction vector mean from the NW in underlying sandstone units towards the NE (Figure 4.56). The difference in paleocurrent direction may just be a reflection of a change in facies from tidally-dominated in the underlying Upper Siq and Quweira Sandstones into fluvially-dominated in this unit (Figure 5.11). Petrographic descriptions

[1] In float

of samples collected from the Saq Sandstone in the Tabuk area show a sublitharenite to quartz arenite sandstone composition, similar to the underlying Quweira Sandstone, with only trace amounts of feldspars (Figure 4.71).



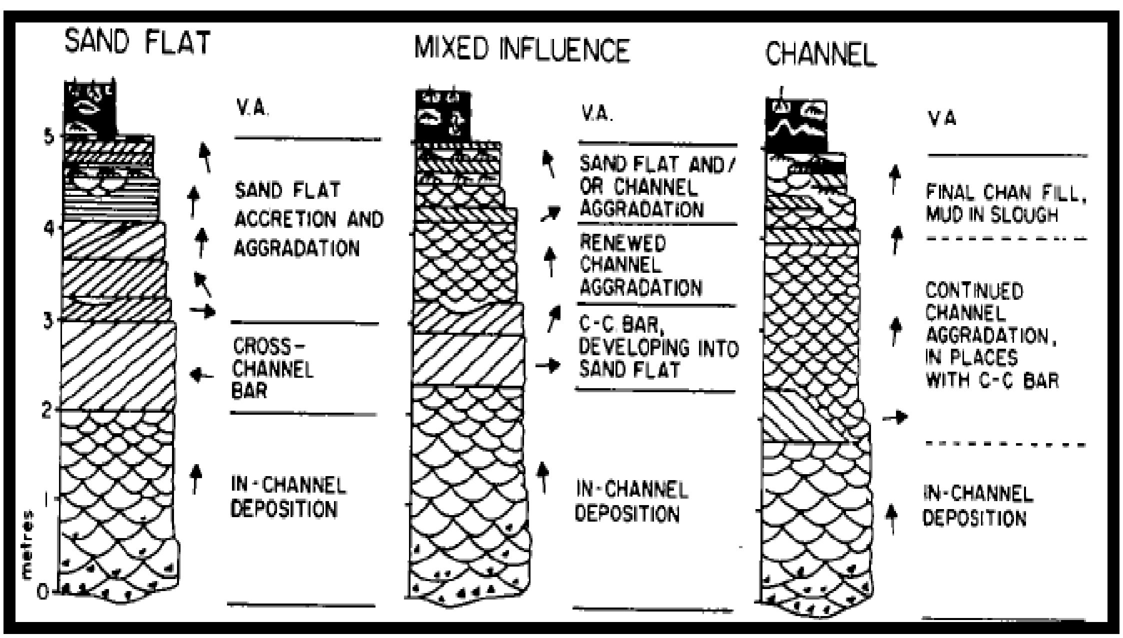


Figure 5.12: 3-D and clastic sequence models of braided-fluvial sand bars, characterizing both in-channel and sand flat deposition, as interpreted in the Devonian Battery Point Formation in the Saskatchewan River (modified after Cant and Walker (1976)).

Figure 5.13: massive sandstone bed showing concentrations of vertical *Skolithos* (measured section T105 at ~19.5 m – Appendix A).

5.2.4 Lithostratigraphic Studies in the Tabuk Area (Summary)

The lithostratigraphic characteristics of the studied Cambro-Ordovician succession in the Tabuk study area can be summarized as follows:

1. The sedimentary succession observed is unconformably overlying the Precambrian basement near the Ash' Shiq area.

2. The succession displays a lithostratigraphic unit that comprises the Upper Siq, Quweira Sandstones and parts of the Saq Sandstone in the Tabuk area. The Lower and Middle Siq Sandstones are missing in this area. Facies associations in this unit show limited fluvial-dominated sequences (FA 1), but are dominated by fining-upward, tidally-influenced deposition (FA 2 and 4). Strong tidal influence is indicated by the presence of thick sets that show thick bundled foresets and double-clay draped foresets (Facies 6). The increased tidal effect is suggestive of a more distal setting within an estuarine, relative to the Al Ula area. Evidence of a rejuvenation of fluvial deposition marks the base of the Saq Sandstone, where the fluvial-dominated deposition (FA 1 and 2) is characterized by Facies 5 deposits indicating braided-channel sand-flat deposition and lacking in-channel deposits. This is characteristically different from underlying sandstone units. Tidally-influenced deposits are limited in this sandstone unit in comparison with underlying sandstones, with beds showing evidence of bioturbation possibly suggestive of periods of marine flooding of an estuary in an overall high-energy fluvial-dominant depositional setting. Evidence of a catastrophic event resulting in the deposition of debris flows suggests tectonic implications such as seismic activity related to the deposition of this unit. Paleocurrent directions show a wide-spread distribution, possibly due to predominantly tidal effect, with a vector mean direction towards the NW. It shows a

major shift from the NW mean vector in the tidally-dominated sandstones towards the NE in the overlying fluvially-dominated sandstones of the Saq. Petrographic analysis shows a progressively-maturing litharenite to quartz arenite sandstone composition (Figure 5.11).

3. Variations in facies associations and distributions throughout this succession are possibly indicative of major changes in the tectonic setting during the Cambro-Ordovician in the presumed marginal setting in the Tabuk area.

5.3 Paleogeographic Variations between the Al Ula and Tabuk Areas

The Cambro-Ordovician sandstone succession shows variations between the two study areas, which are located at a distance of approximately 270 km apart (Figure 3.1).

In the context of lithostratigraphy, correlations can be made between the successions observed in both the Al Ula and Tabuk areas. This correlation comprises the Upper Siq, Quweira and Saq Sandstones. The Lower and Middle Siq Sandstones are limited to the Al Ula area and are missing in the Tabuk area. This correlation is based on observed depositional facies, facies associations, paleocurrent analysis and petrographic descriptions (Figure 5.10 and Figure 5.11).

In the two study areas, the correlated succession is dominated by both high-energy fluvial and tidally-influenced deposition. Increased tidal-influence input characterizes the succession in the Tabuk area, possibly due to its more distal setting with respect to the Al Ula area. Paleocurrent flow directions show a consistent mean vector direction towards the NW that shifts in places towards the NE possibly due slight tectonic or paleogeographic variations deriving unique facies distributions. However, these deposits show similar petrographic descriptions, characterized by feldspar-free sandstone compositions, suggestive of a consistent sedimentary source.

The Lower and Middle Siq Sandstones in the Al Ula area are excluded from this correlation because they represent a unique low-energy fluvial and tidally-influenced deposition, with a more arkosic sandstone composition. These two sandstone units are considered to represent a different, possibly underlying lithostratigraphic unit in this study area.

Figure 5.14 summarizes this lithostratigraphic correlation between the two study areas.

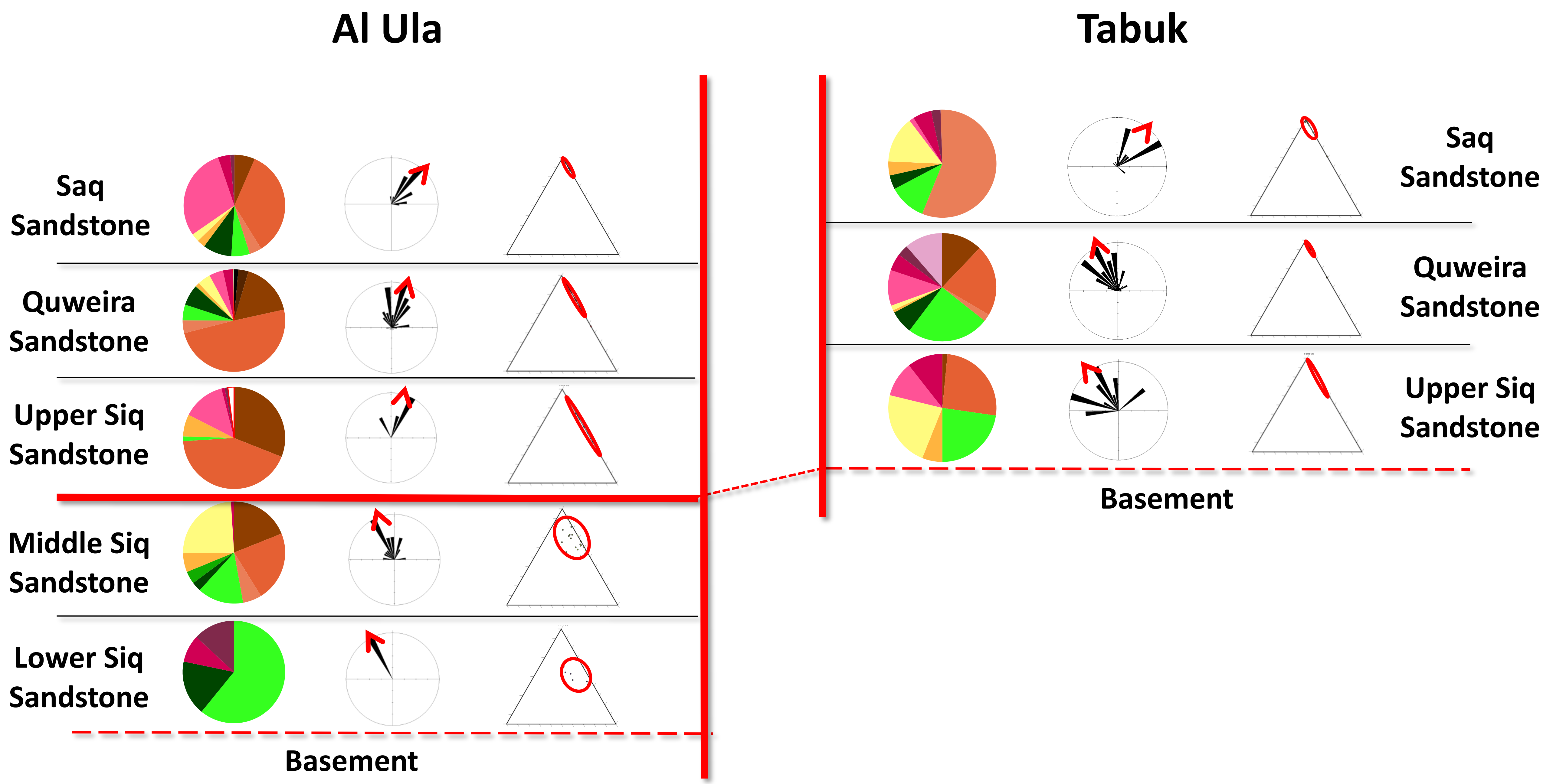


Figure 5.14: Summary of the different lithostratigraphic units studied the Al Ula and Tabuk areas with a possible correlation between equivalent units.

CHAPTER 6

CONCLUSIONS

Lithostratigraphic studies of the Cambro-Ordovician sandstone succession, which unconformably overlie the Precambrian basement, identify a number of different units in the Al Ula and Tabuk areas. These different lithostratigraphic units are characterized by changes in depositional facies and facies associations, paleocurrent direction changes and sandstone petrographic variations. The integration of these data helped identify two lithostratigraphic units in both study areas with a possible correlation between these areas.

The first lithostratigraphic unit, identified only in the Al Ula study area, comprises of the Lower and Middle Siq Sandstones. This unit is characterized by the overall limited high-energy braided-fluvial in-channel deposition, and a more variable, progressively waning tidal-influence in a fluvial-tidal interaction setting within an estuarine. Paleocurrent directions show a consistent NW flow direction. Petrographic analysis identifies clearly a feldspathic litharenite sandstone composition in these rocks.

The second lithostratigraphic unit is identified in both study areas. It comprises the Upper Siq, Quweira and Saq Sandstones. This unit is characterized by high-energy braided-fluvial in-channel (limited sand-flat) deposition with variable high-energy tidally-influenced and tidally-dominated deposition. Distribution of tidally-influenced deposits is more abundant in the Tabuk area, most likely due to variations in proximality between the two study areas (The Tabuk area is the more distal). Evidence of deformation has been observed in this unit in both study areas, and catastrophic deposition has been observed in the Tabuk area. Paleocurrent flow directions in this lithostratigraphic unit show inconsistency between the two study areas, probably due to observed differences in facies and hence depositional settings. The increased tidal influence in the Tabuk study area results in a more wide-spread distribution of paleocurrent direction readings. These sandstones show feldspar to be essentially absent in litharenite to quartz litharenite sandstones.

The overall interpretations and conclusions reflecting to these Cambro-Ordovician sandstones suggest a high-energy braided-fluvial channel deposition with variable tidal influence within a fluvio-estuarine depositional environment. Studied variations in depositional facies, facies associations and facies distribution, in addition to paleocurrent and petrographic properties, demonstrating paleogeographic distinctions are strong indications of the significant role of tectonic fluctuations within the basin during the Cambro-Ordovician time. Investigations of such basinal adjustments could be the scope for future work.

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VITAE

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Abdullah Wahbi is a clastic sedimentologist working in the Reservoir Characterization Department in Saudi Aramco in Dhahran, Saudi Arabia. After completing high school, He was awarded a full scholarship through the Saudi Aramco College Degree Program for Non-Employees (CDPNE). He started his Bachelor's degree program in Geology at Louisiana State University in Baton Rouge, Louisiana in the United States of America in August 2005. Upon his graduation in August 2009, he started his career in Saudi Aramco, holding various positions in the company as a geosteering geologist, wellsite geologist and reservoir geologist. In July 2011, Abdullah was nominated to become a member in the Saudi Aramco Exploration's Specialist Development Program (SDP), a program designed to support the technical development and specialization of young talents in the company. With clastic sedimentology as his selected specialty, he develops facies descriptions and conceptual lithostratigraphic subsurface models relying primarily on core descriptions that are ultimately utilized in fully-integrated reservoir models. In addition to his professional career at Saudi Aramco, Abdullah Wahbi started his part-time graduate program in February 2010 at King Fahd University of Petroleum and Minerals (KFUPM), studying for his Master's degree in Geology. He is a member in the Dhahran Geological Society (DGS), the American Association of Petroleum Geology (AAPG) and the International Association of Sedimentologists (IAS).

SEDIMENTOLOGICAL AND STRATIGRAPHIC STUDIES OF THE CAMBRO-ORDOVICIAN SUCCESSION IN NORTHWEST SAUDI ARABIA

APPENDIX A

BY

ABDULLAH MOHAMMEDFAIZ WAHBI

VOLUME II

EARTH SCIENCES DEPARTMENT

MAY 2014

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STUDY AREAS

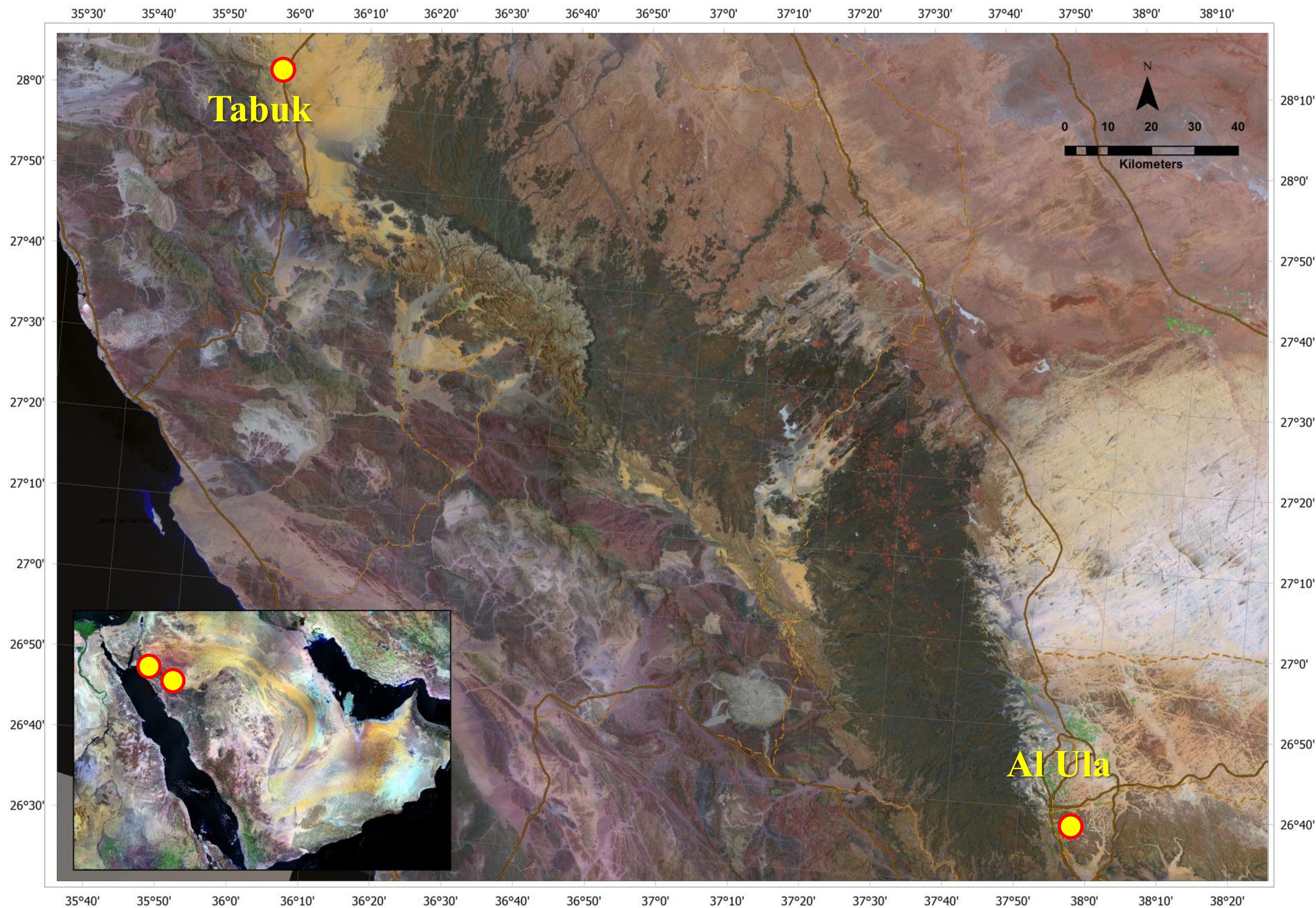


Figure 1: Map of northwest of Saudi Arabia highlighting the locations of the two study areas in this study near both Al Ula and Tabuk (estimated distance between the two study areas is 270 km).

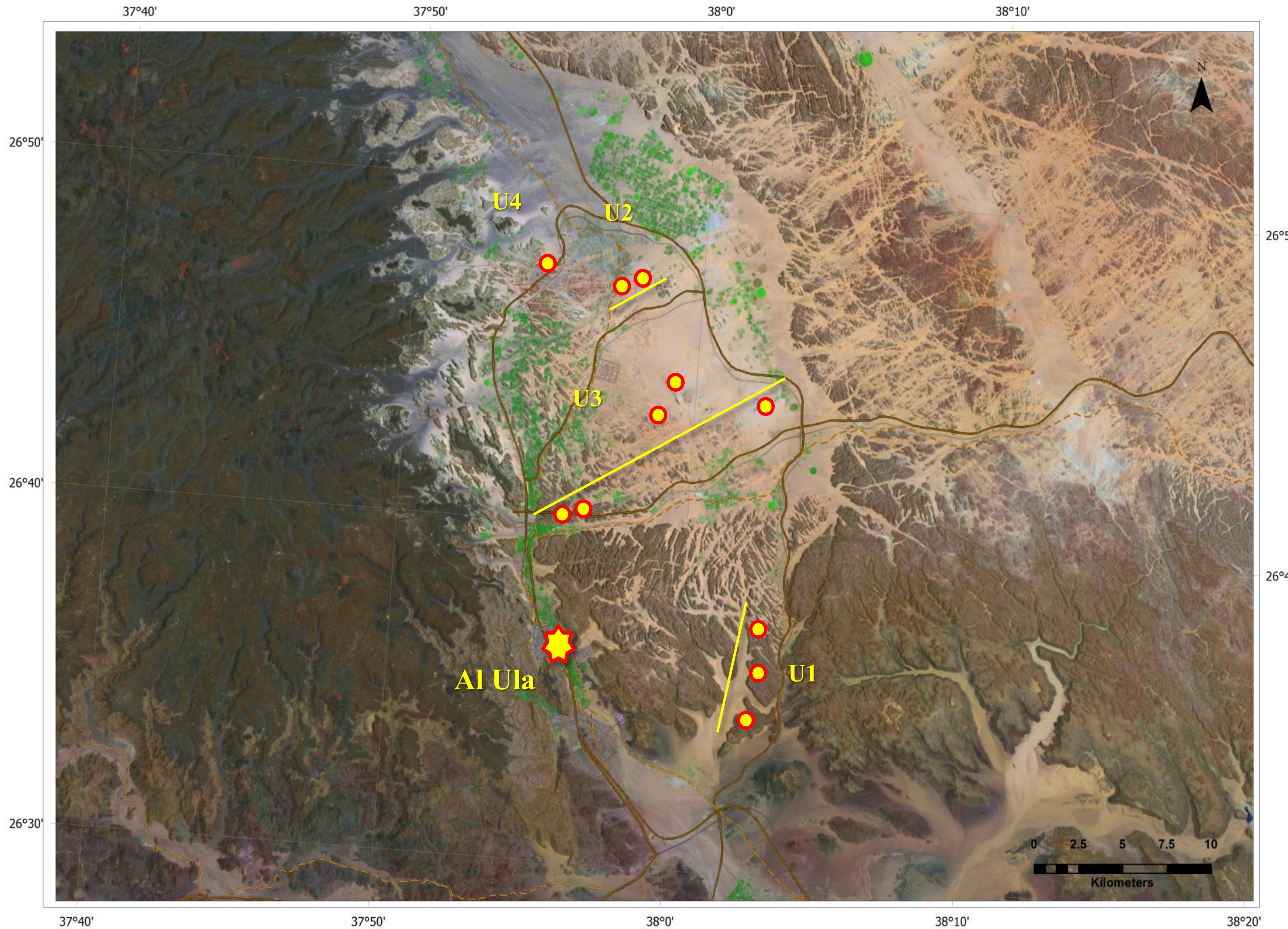


Figure 2: Map displaying locations of measured sections in the Al Ula study area (except for area U5).

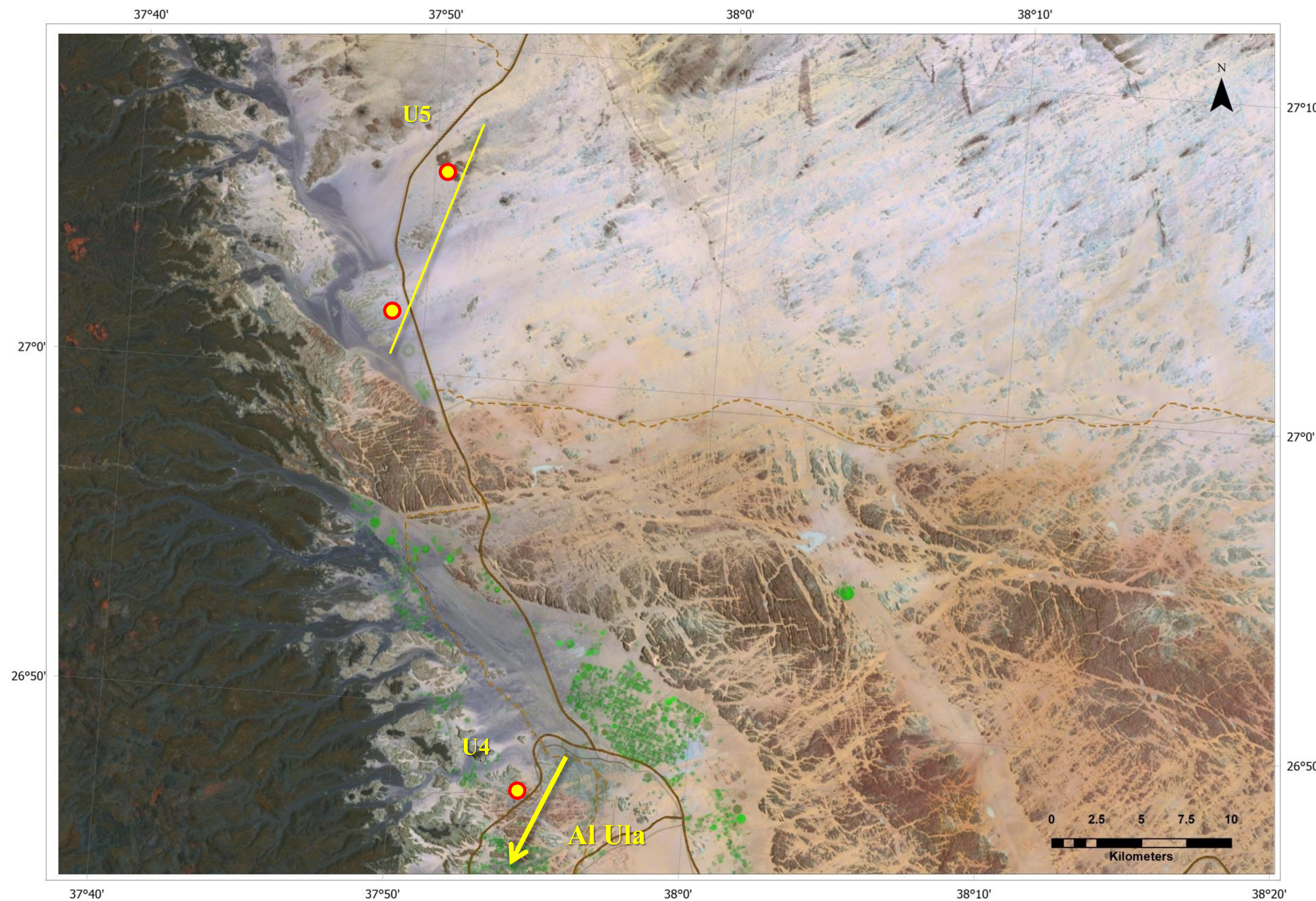


Figure 3: Map displaying the northern part of the Al Ula study area, showing the location of areas U5 and U4 for reference. The arrow shows the direction towards Al Ula.

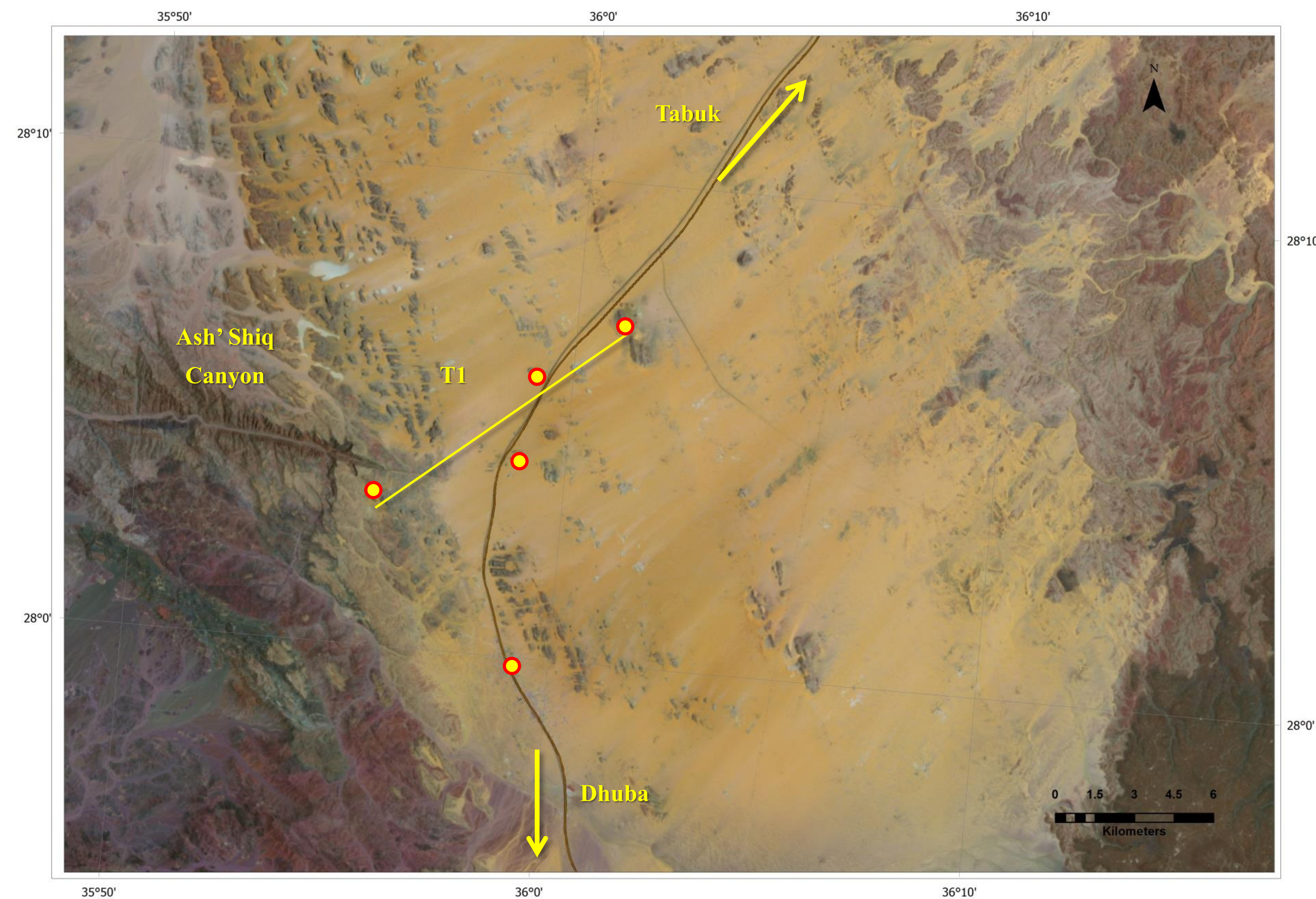


Figure 4: Map displaying locations of measured sections in the Tabuk study area with reference to the location of (Shai'b) Ash' Shiq (Canyon), located southwest of the city of Tabuk. Arrows show directions towards both Tabuk and Dhuba.

DEPOSITIONAL FACIES

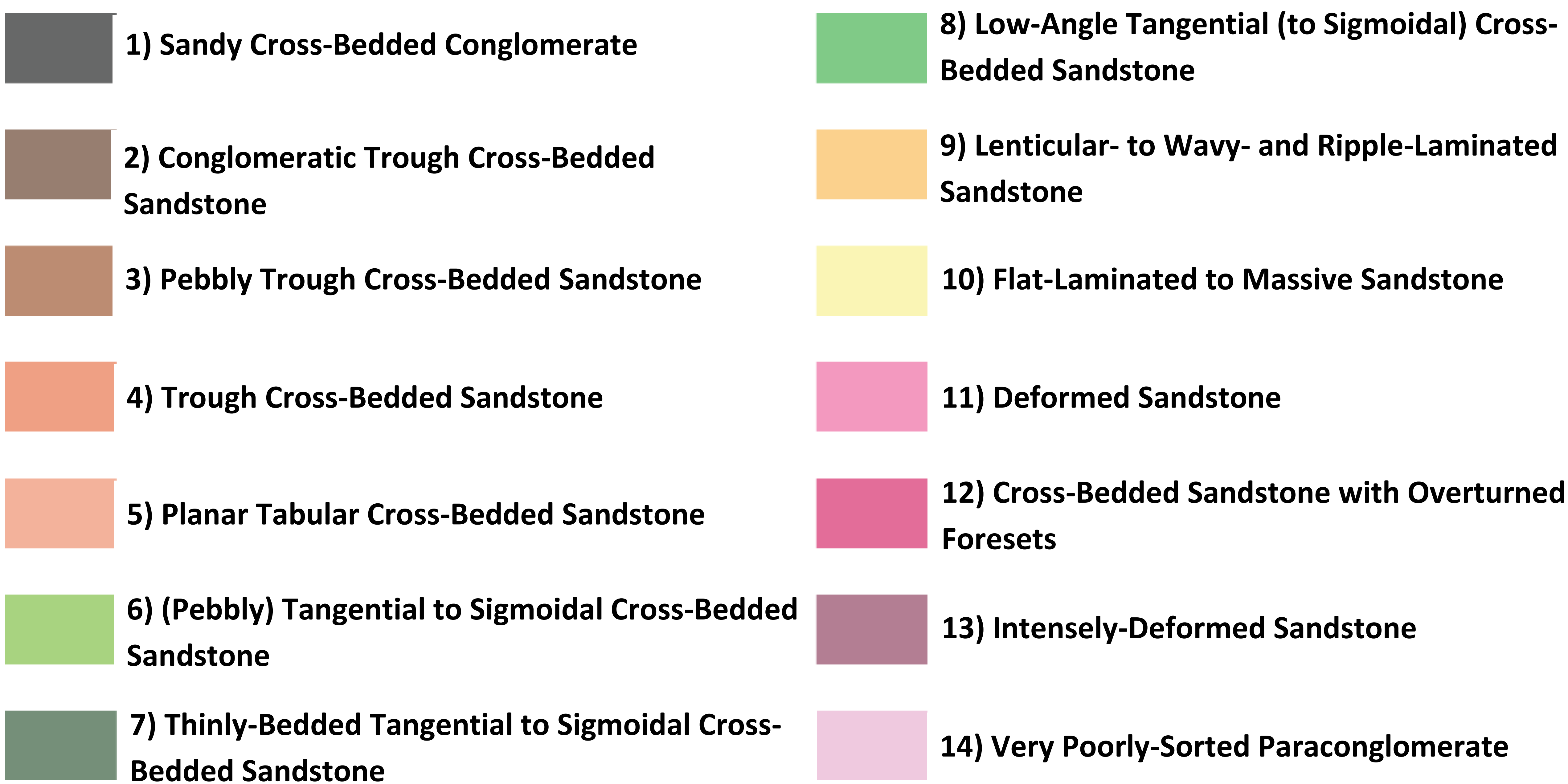


Figure 5: Described depositional facies, numbered and color-coded as they appear in this study

MEASURED SECTIONS

Table 1: Summary of measured sections in the Al Ula area

Line of Section	Measured Section	Location Remarks	Coordinates (dd° mm.mmm’)
U1	U101	Wadi east of the town of Al Ula. Composite section lay conformably on top of basement and measured sections are stratigraphically in succession	N 26° 34.718’, E 38° 02.065’
	U102		N 26° 36.405’, E 38° 02.533’
	U103		N 26° 37.468’, E 38° 02.337’
U2	U201	Al Khuraimat (Mada’in Saleh)	N 26° 46.934’, E 37° 56.759’
	U202a	Ad Diwan (Mada’in Saleh)	N 26° 47.571’, E 37° 57.739’
	U202b		N 26° 47.380’, E 37° 57.950’
U3	U301	Aligned with the start of Highway-70 north of Al Ula and heading east toward Ha’il	N 26° 39.961’, E 37° 55.345’
	U302		N 26° 40.195’, E 37° 56.238’
	U303		N 26° 43.313’, E 37° 58.679’
	U304		N 26° 44.186’, E 37° 59.022’
	U305		N 26° 44.000’, E 38° 02.300’
U4	U401	Continuous succession is commonly covered by Tertiary lava flow deposits	N 26° 47.579’, E 37° 54.589’
U5	U501a	Area further north of Al Ula (~ 55 km) where morphology of outcrops changes	N 27° 02.126’, E 37° 48.999’
	U501b		N 27° 01.858°, E 37° 48.828’
	U502		N 27° 07.440’, E 37° 50.693’

Table 2: Summary of measured sections in the Tabuk area

Line of Section	Measured Section	Location Remarks	Coordinates (dd° mm.mmm’)
T1	T101	As’ Siq (pronounced: Ash’ Shiq) reference section (Bramkamp et al, 1963)	N 28° 03.287’, E 35° 55.629’
	T102	Outcrop behind Shegri Gas Station, Shegri Village, Tabuk	N 27° 59.901’, E 35° 59.200’
	T103a, b	Off Highway-80 heading east from Bajdah towards Tabuk	N 28° 04.017’, E 35° 58.964’
	T104		N 28° 06.004’, E 35° 59.072’
	T105		N 28° 07.200’, E 36° 00.816’

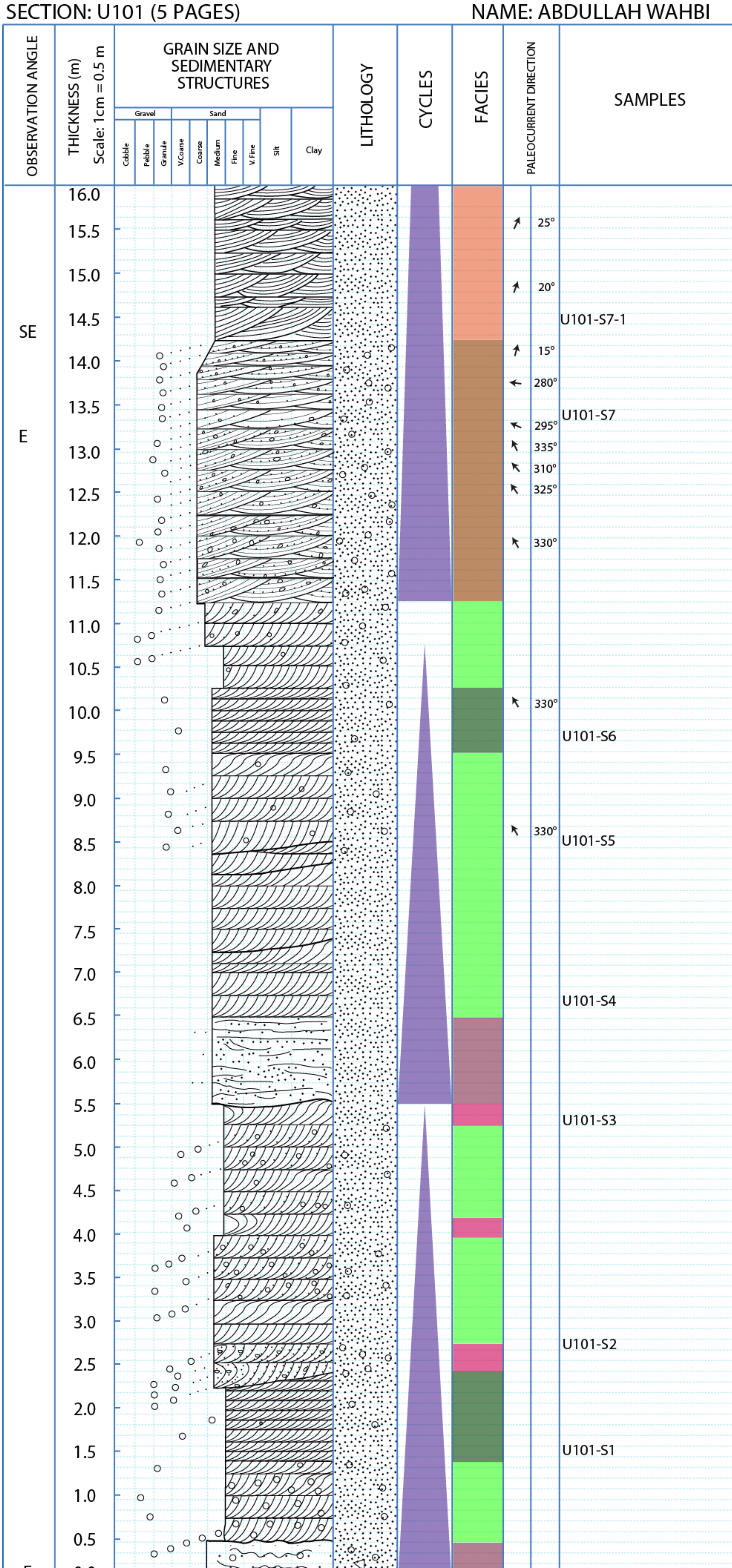
3.1 AL ULA STUDY AREA

CITY/TOWN: Al Ula

SECTION: U101 (5 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 34.718′, E 38° 02.065′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: red-purple to pink; medium (u)- to coarse (u)-grained; poorly-sorted; sub- angular to sub-rounded; trough cross-bedded sets (<10-30 cm thick; up to 2 m-wide); random distribution of sand- to pebble-size quartz (sub-rounded, up to 4 cm in size)

TANGENTIAL CROSS-BEDDED SANDSTONE: red to reddish brown; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; tangential cross-bedded sets (20-30 cm thick); truncations and scours are abundant; CROSS-BEDDED SANDSTONES WITH OVERTURNED FORESETS are observed in places; bedding shows minor, randomly distributed inclusions of sand- to pebble-size of quartz with rare feldspars (up to 4 cm in size), angular and elongated; basal bed is medium (u)-grained INTENSELY-DEFORMED SANDSTONE; minor development into THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE (<10 cm thick sets)

SIGMOIDAL TO TANGENTIAL CROSS-BEDDED SANDSTONE: red to reddish brown; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; sigmoidal cross-bedded sets that develop tangential cross-bedded sets in places (20-40 cm thick); truncations are abundant; CROSS-BEDDED SANDSTONES WITH OVERTURNED FORESETS are observed in places; random distribution of sand- to pebble-size quartz and feldspars (2-5 cm in size; angular to well-rounded); basal bed is coarse (l)-grained INTENSELY-DEFORMED SANDSTONE with minor inclusions of sand- to pebble-size quartz, feldspars and rare granitic fragments (up to 5 cm in size); succession evolves into THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE (<10 cm thick sets)

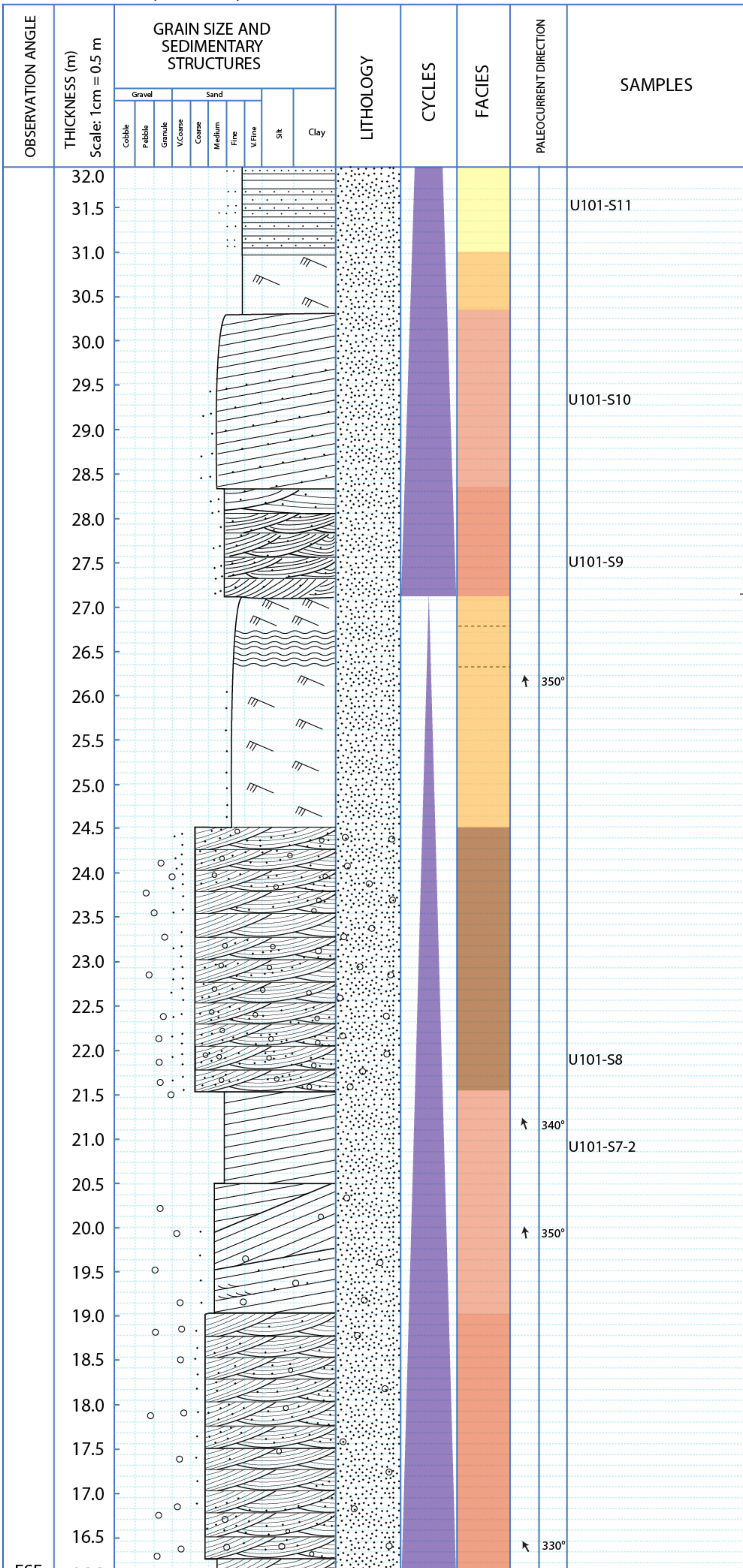
CITY/TOWN: Al Ula

PAGE 2 OF 5

SECTION: U101 (5 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 34.718', E 38° 02.065'



DESCRIPTION / REMARKS

PLANER TABULAR CROSS-BEDDED SANDSTONE: red-purple; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; planer tabular cross-bedded set (150 cm thick); fining-upward trend; concentrations of sand-size quartz grains at bases of foresets; evolves into RIPPLE- to FLAT-LAMINATED SANDSTONE beds

TROUGH CROSS-BEDDED SANDSTONE: red-purple to pink; medium (l)-grained; moderately-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10 cm thick); distribution of coarser sand-size quartz grains at bases of foresets

LENTICULAR- TO RIPPLE- AND WAVY-LAMINATED SANDSTONE: tan, pink to reddish; fine (l & u)-grained; well- to moderately-sorted; sub- to well-rounded; discontinuous lenticular- to ripple- and wavy-laminated sandstone beds; sand lenses observed show continuous coarser-sand lamina; wavy laminations show back ripples in places

PEBBLY TROUGH CROSS-BEDDED SANDSTONE: red-purple to pink; medium (u)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-25 cm thick); fining-upward trend; show random distribution of sand- to pebble-size quartz

PLANER TABULAR CROSS-BEDDED SANDSTONE: red-purple; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; planer tabular cross-bedded sets (40-50 cm thick); fining-upward trend; evidence of discordance; back-flow structures observed; random distribution of sand- to pebble-size quartz

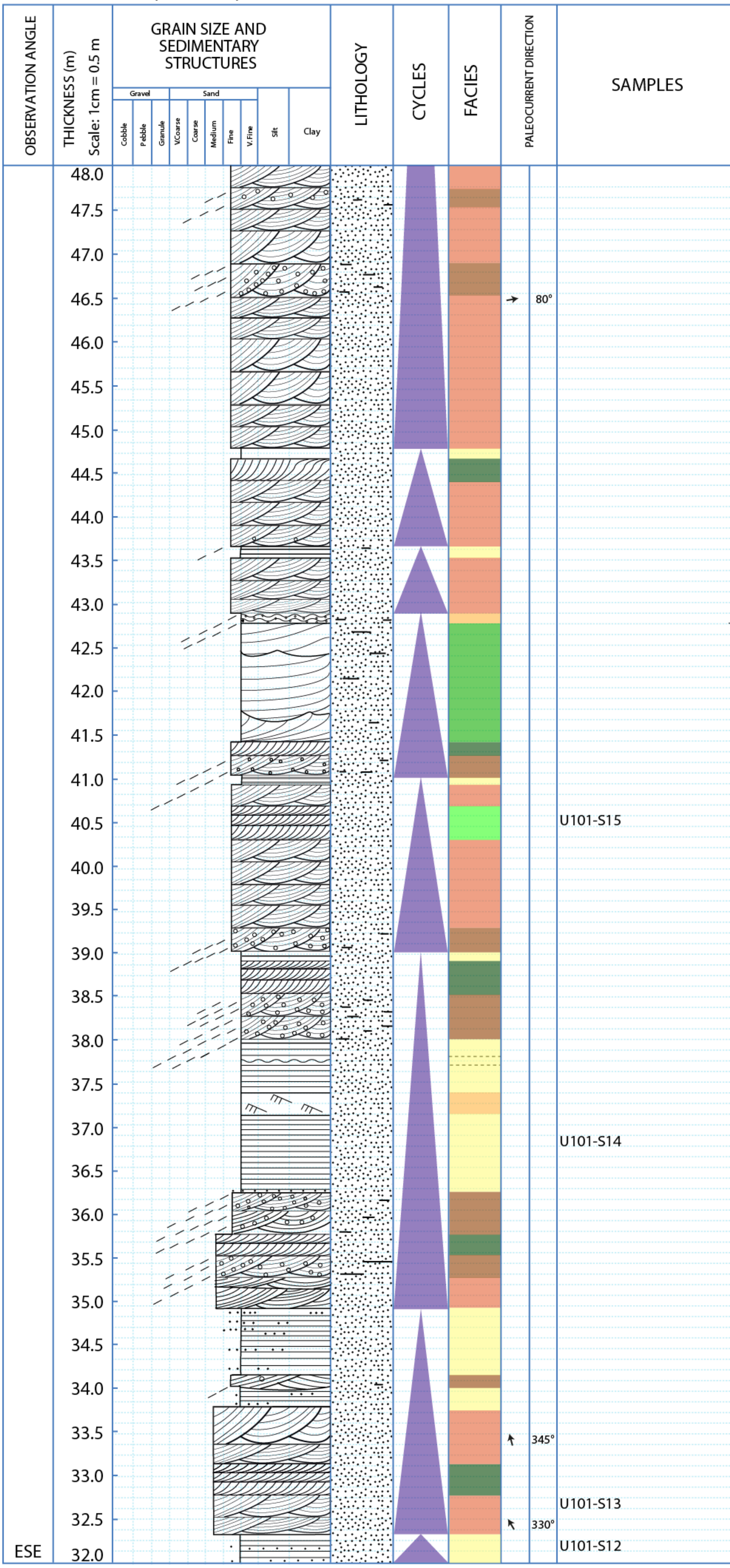
TROUGH CROSS-BEDDED SANDSTONE: red-purple to pink; medium (u)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-25 cm thick); show random distribution of sand- to pebble-size quartz

CITY/TOWN: Al Ula

SECTION: U101 (5 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 34.718′, E 38° 02.065′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish pink; fine (u)-grained; well- to moderately-sorted; sub- to well-rounded; cycles start with (pebbly) trough cross-bedded sets (10-30 cm thick); abundance of truncations at bases of sets and beds; some sets show significant concentrations of mud clasts (well-rounded to elongated, 1-4 cm in size) at bases of foresets and randomly distributed; succession develops into TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE and MASSIVE TO FLAT-LAMINATED SANDSTONE beds

LOW-ANGLE TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE: tan, red to pink; fine (l)-grained, silty and argillaceous; well-sorted; sub- to well-rounded; three low-angle tangential to sigmoidal cross-bedded sets (10-30 cm thick); mud drapes formed at bases of foresets; sets show relatively deeper scour; bedding evolves into WAVY-LAMINATED SANDSTONE beds with abundance of mud-clast granules

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish pink; medium (l and u)-grained; well- to moderately-sorted; sub- to well-rounded; cycles start with (pebbly) trough cross-bedded sets (<10-30 cm thick); abundance of truncations at bases of sets and beds; some sets show significant concentrations of mud clasts (well-rounded to elongated, 1-4 cm in size) at bases of foresets and randomly distributed; cycles develop THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSOTNE and fine (l)- to medium (u)-grained FLAT-LAMINATED SANDSTONE beds which show bundled foresets (41.0 m)

WAVY- TO RIPPLE- AND FLAT-LAMINATED SANDSTONE: tan to reddish pink; fine (l)-grained, silty; well- to moderately-sorted; sub- to well-rounded; alternations between the two facies with subtle variations in lamina thickness and grain size; back ripples are observed in places

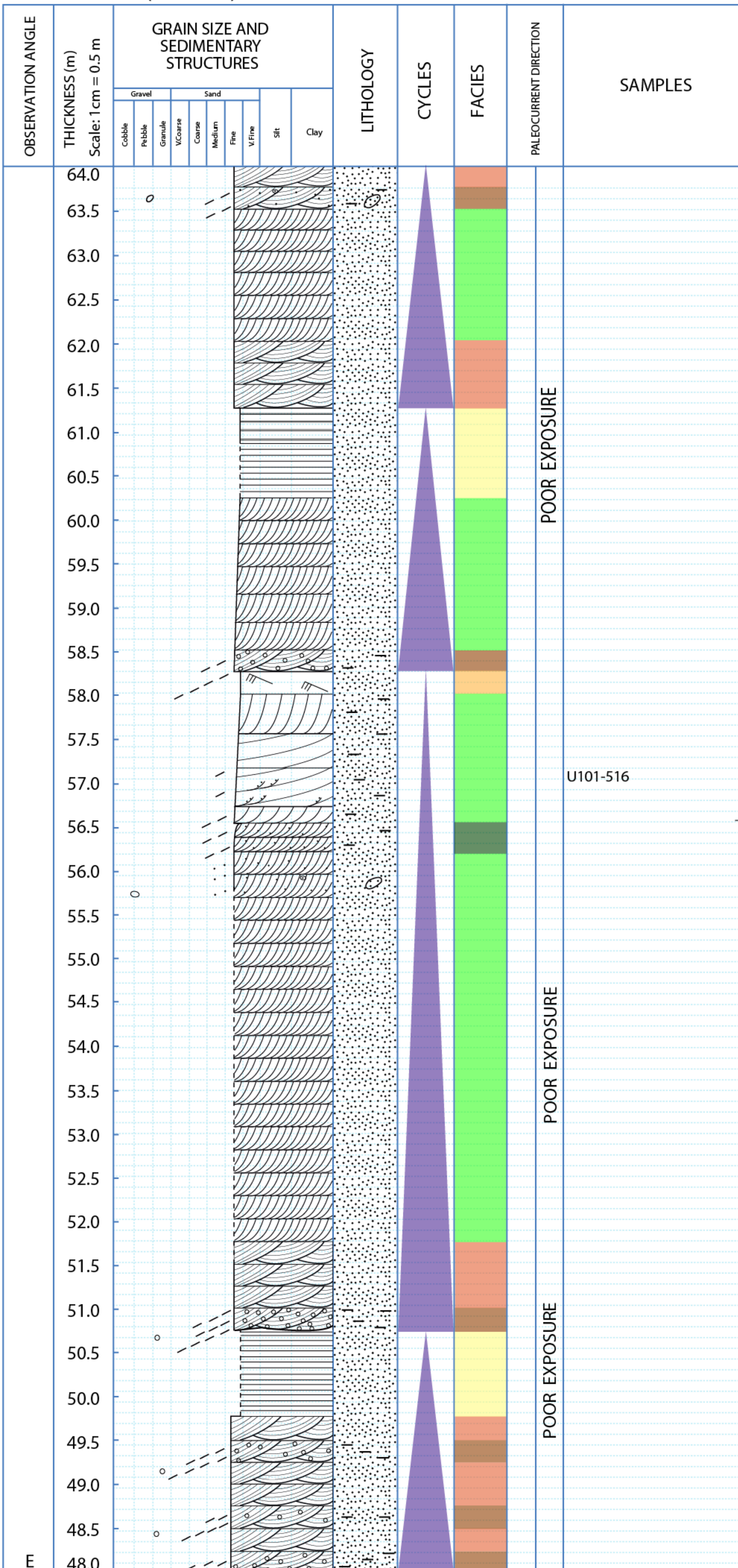
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish pink; medium (u)-grained; well- to moderately-sorted; sub- to well-rounded; cycles start with trough cross-bedded sets (<10-30 cm thick); abundance of truncations at bases of sets and beds; some sets show significant concentrations of mud clasts (well-rounded to elongated, 1-4 cm in size), concentrated at bases of foresets and randomly distributed; cycles develop fine (l)- to medium (l)-grained THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE and FLAT-LAMINATED SANDSTONE beds

CITY/TOWN: Al Ula

SECTION: U101 (5 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 34.718', E 38° 02.065'



DESCRIPTION / REMARKS

(PEBBLY) TROUGH AND TANGENTIAL CROSS-BEDDED SANDSTONE: orange, reddish pink; fine (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; cycles start with (pebbly) trough cross-bedded sets (10-20 cm thick); bedding shows concentrations of sand- to pebble-size mud clasts (up to 4 cm in size; rare quartz and sandstone clasts) at bases of cycles; succession develops tangential cross-bedded sets (<10-20 cm thick); fining-upward into FLAT-LAMINATED SANDSTONE beds which display bundled-foresets in places

(LOW-ANGLE) TANGENTIAL CROSS-BEDDED SANDSTONE: reddish pink; fine (l and u)-grained, silty and argillaceous; well- to moderately-sorted; sub-rounded to rounded; low-angle tangential cross-bedded sets (20-50 cm thick); mud clasts and mud drapes observed at bases of sets and foresets; minor scouring; bedding topped by RIPPLE-LAMINATED SANDSTONE beds

(PEBBLY) TROUGH AND TANGENTIAL CROSS-BEDDED SANDSTONE: orange, reddish pink; fine (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; cycles start with (pebbly) trough cross-bedded sets (10-20 cm thick); bedding shows concentrations of sand- to pebble-size mud clasts (up to 4 cm in size; rare quartz and sandstone clasts) at bases of cycles; succession develops (thinly-bedded) tangential cross-bedded sandstone sets (<10-20 cm thick)

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: orange, reddish pink; fine (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; cycles start with (pebbly) trough cross-bedded sets (10-20 cm thick); bedding shows concentrations of sand- to pebble-size mud clasts (up to 4 cm in size; rare quartz and sandstone clasts) at bases of cycles and sets; fining-upward into FLAT-LAMINATED SANDSTONE beds at tops of cycles

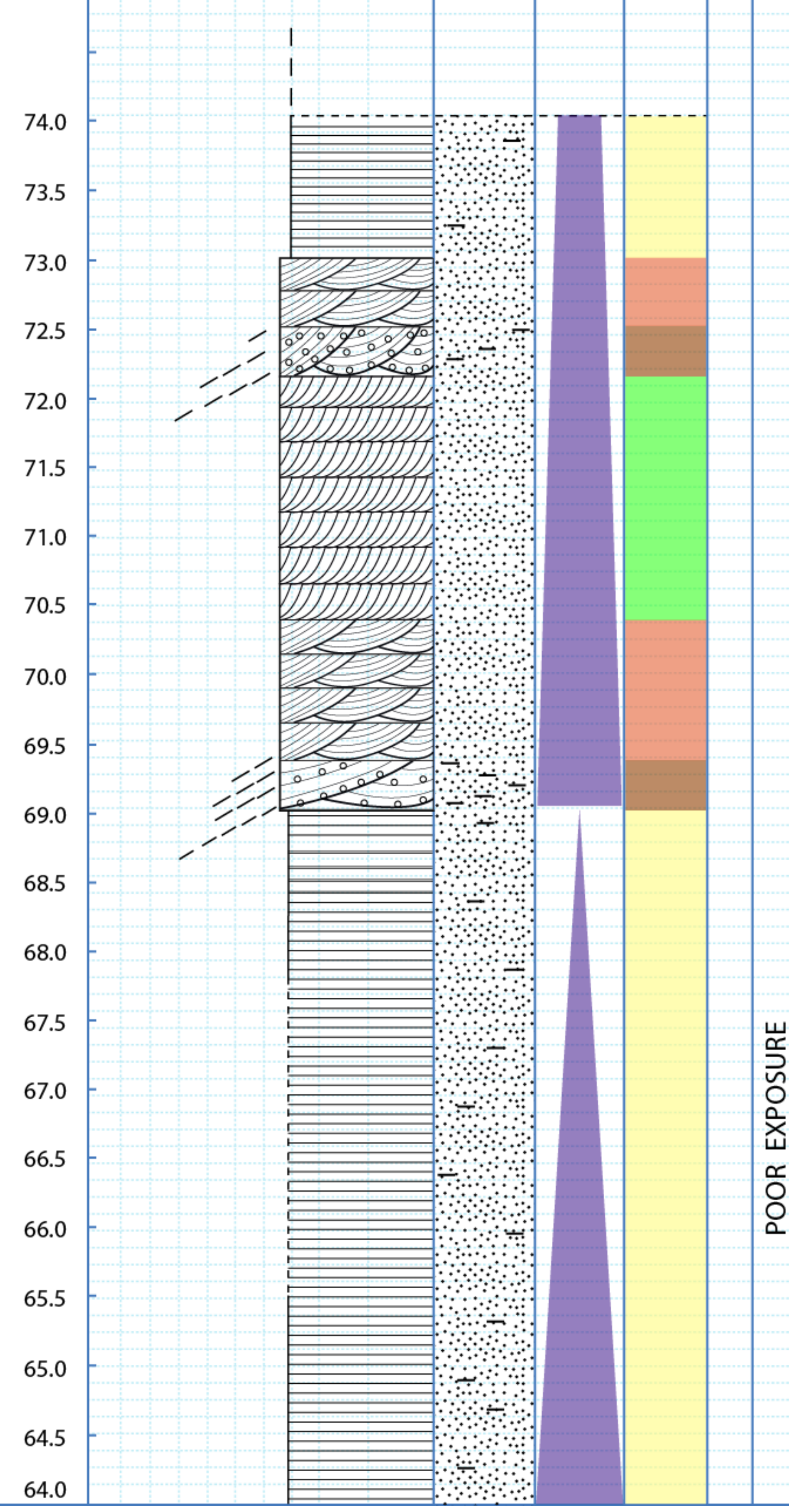
CITY/TOWN: Al Ula

SECTION: U101 (5 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 34.718′, E 38° 02.065′

OBSERVATION ANGLE | THICKNESS (m) Scale: 1cm = 0.5 m | GRAIN SIZE AND SEDIMENTARY STRUCTURES (Gravel: Cobble, Pebble, Granule; Sand: V.Coarse, Coarse, Medium, Fine, V.Fine; Silt; Clay) | LITHOLOGY | CYCLES | FACIES | PALEOCURRENT DIRECTION | SAMPLES | DESCRIPTION / REMARKS



E

SAMPLES: U101-S18 (at about 72.5 m); U101-S17 (at about 68.5 m)

NOTE: Exposure in the following 15-20 m is covered by scree and is difficult to describe. Bedding shows alternations between (PEBBLY) TROUGH CROSS-BEDDED SANDSTONE and (SILTY TO ARGILLACEOUS) FLAT-LAMINATED SANDSTONE beds. Trough cross-bedded sets become finer-grained with thinner sets, while flat-laminated bedding becomes thicker. Above this sequence, trough cross-bedded sandstone beds are continuous with thicker beds/sets, with gradual disappearance of mud clasts. This contact is correlated with base of section U102

(PEBBLY) TROUGH AND TANGENTIAL CROSS-BEDDED SANDSTONE: white, reddish-pink; fine (l and u)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (~20 cm thick); bases of sets show concentrations of pebble-size mud clasts with various shapes; development into tangential cross-bedded sets (~20 cm thick); cycles topped by variegated, fine (l)-grained, silty to argillaceous FLAT-LAMINATED SANDSTONE beds; poor cementation in places

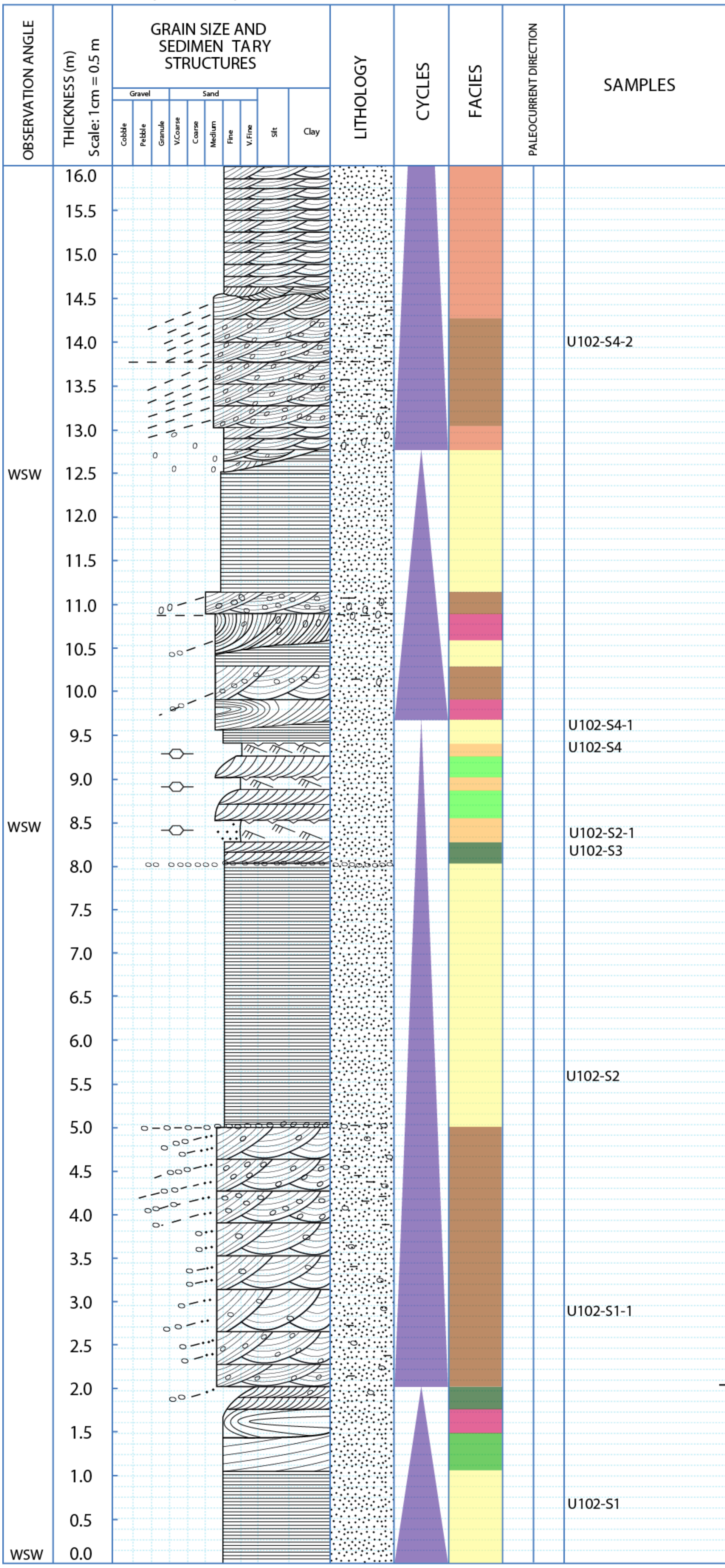
FLAT-LAMINATED SANDSTONE: variegated; fine (l)-grained, silty and argillaceous; well- to moderately-sorted; sub-rounded to rounded; flat-laminated sandstone beds with some sets displaying bundled-foresets; poor cementation in places

CITY/TOWN: Al Ula

SECTION: U102 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 36.405′, E 38° 02.533′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: reddish-brown to orange color; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-30 cm thick); truncations are abundant; bedding shows concentrations of pebble-size quartz and mud clasts along bases of foresets, sets and beds; minor display of CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS; cycles evolve into FLAT-LAMINATED SANDSTONE (finer grain size, silty to argillaceous, show bundle-foresets in places); lags show concentrations of mud clasts

FLAT-LAMINATED SANDSTONE: reddish-brown and pink, grey weathering; fine (l)- to medium (l)-grained; moderately-sorted (bimodally-sorted); sub-angular to rounded; flat-laminated sandstone beds (coarser-grained lamina are more quartz-rich); evolves into alterations between (THINLY-BEDDED) TANGENTIAL CROSS-BEDDED SANDSTONE beds (minor display of pebbles) and LENTICULAR- TO RIPPLE-LAMINATED SANDSOTNE beds (discontinuous to continuous laminations; back-ripples; topped by mud cracks and desiccation surfaces); lags show concentrations of pebble-size quartz and mud clasts

PEBBLY TROUGH CROSS-BEDDED SANDSTONE: reddish-brown to beige; medium (u)-grained; moderately-sorted; sub-angular to sub-rounded; trough cross-bedded sets (20-50 cm thick) truncating overlain deposits; show concentrations of sand- to pebble-size, well-rounded to elongated quartz and mud clasts

FLAT-LAMINATED SANDSTONE: reddish-brown to pink, fine (u)- to medium (l)-grained; moderately-sorted; sub-angular to sub-rounded; flat-laminated sandstone beds; lamina alternate between dark and bright color with alternation of grain size (ml-fu) (bimodal sorting?); fining-upward sequence topped by CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS, LOW-ANGLE TANGENTIAL CROSS-BEDDED SANDSOTNE and THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE beds (ml grain size) showing a minor well-rounded quartz pebbles; well cemented

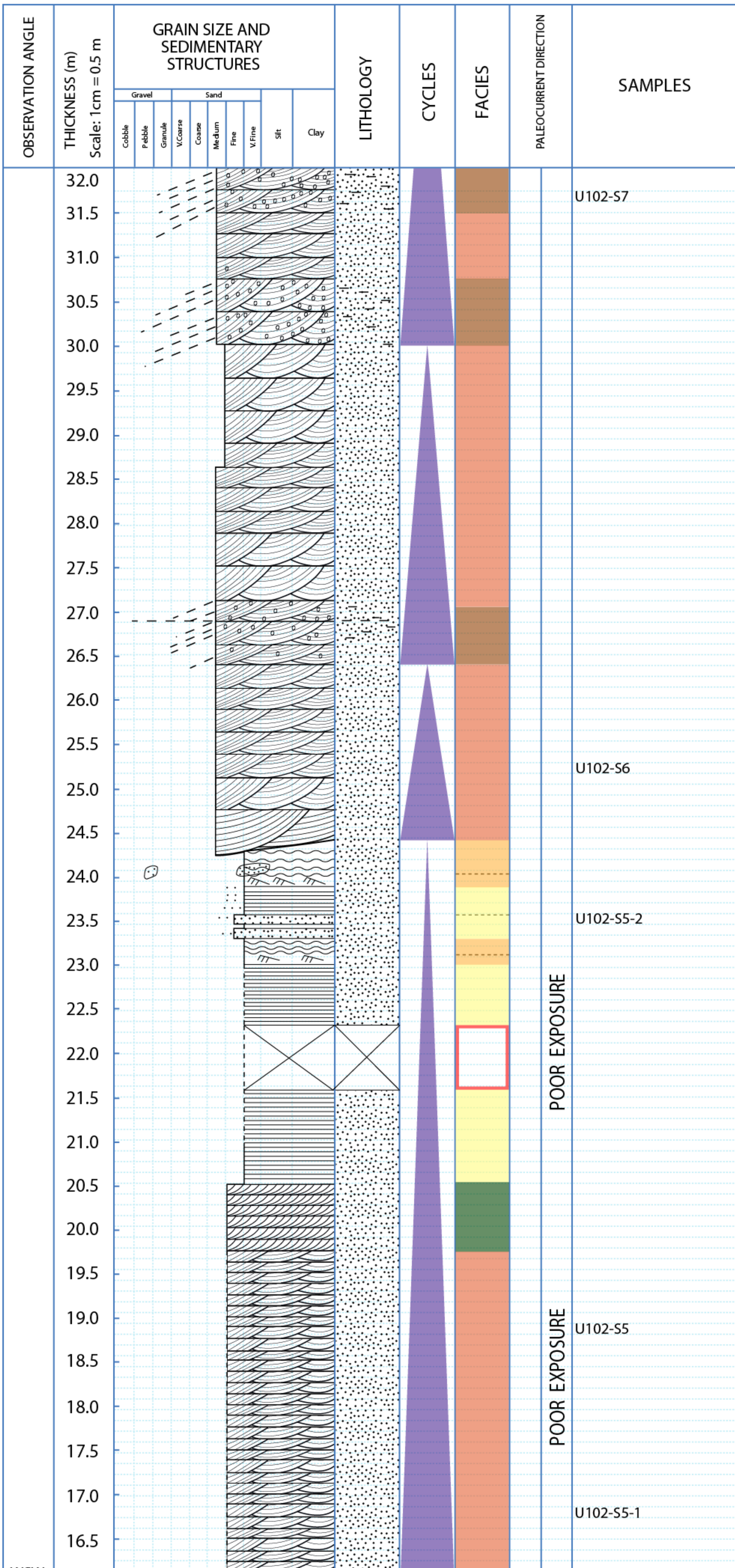
CITY/TOWN: Al Ula

SECTION: U102 (3 PAGES)

NAME: ABDULLAH WAHBI

PAGE 2 OF 3

LOCATION: N 26° 36.405′, E 38° 02.533′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: beige to orange color; medium (l and u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; (pebbly) trough cross-bedded sets (20-50 cm thick); some beds show concentrations of mud clasts at bases of sets and foresets; lags display pebble-size mud clasts

FLAT-LAMINATED TO MASSIVE SANDSTONE: beige to pink layers; fine (l and u)-grained, silty and argillaceous; moderately- to poorly-sorted; sub-angular to sub-rounded; bimodally-grained flat-laminated to massive sandstone beds; bedding evolves into LENTICULAR-, RIPPLE- TO WAVY-LAMINATED SANDSTONE (discontinuous to continuous; sandy layers; display pebble-size sandstone clasts – slump; at 24.0 m); poor exposure

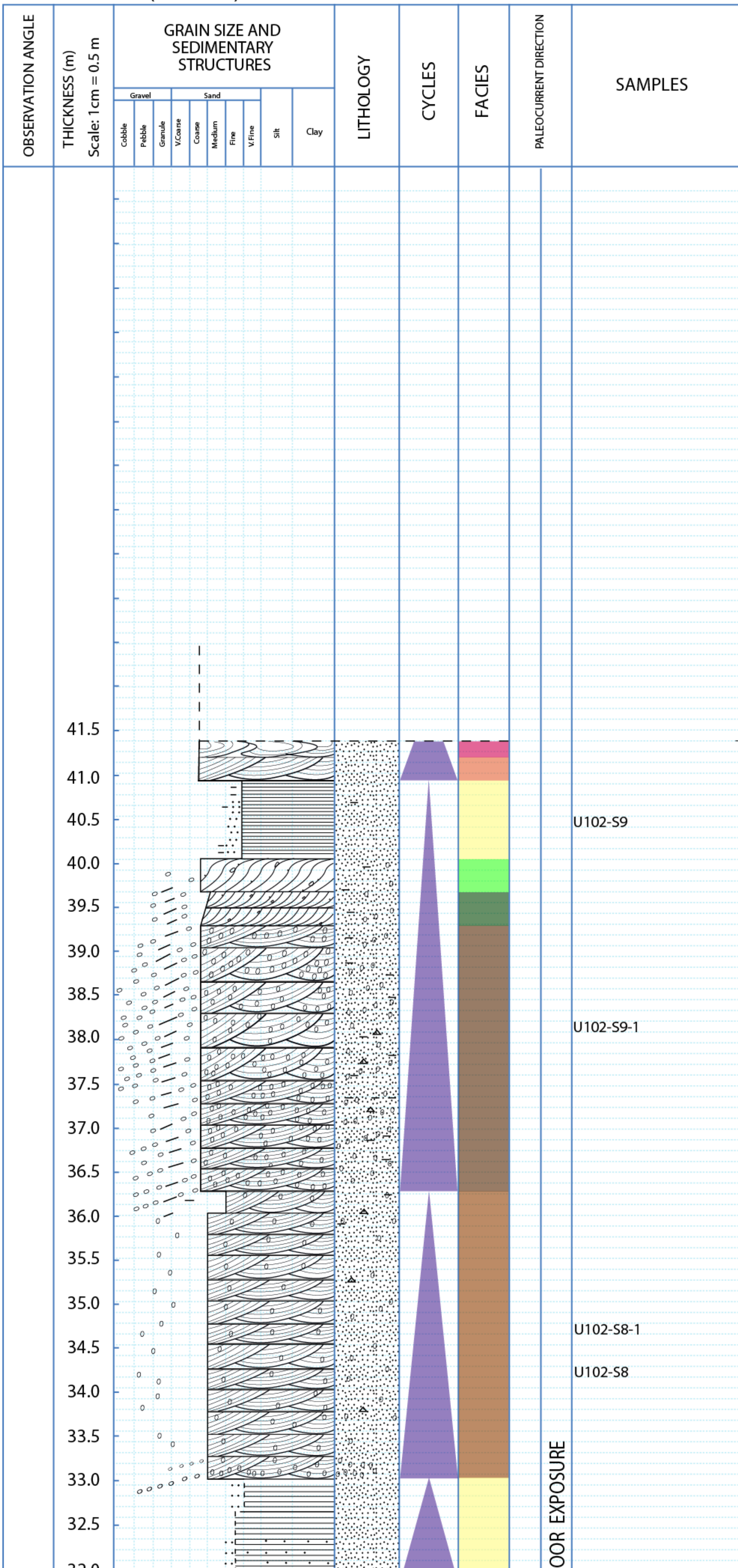
TROUGH CROSS-BEDDED SANDSTONE: reddish-brown to orange; medium (l)-grained; moderately-sorted; sub-angular to sub-rounded; thin trough cross-bedded sets (up to 10 cm thick); develops THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE sets; poor exposure

CITY/TOWN: Al Ula

SECTION: U102 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 36.405', E 38° 02.533'



DESCRIPTION / REMARKS

FLAT-LAMINATED SANDSTONE: beige, pink and dark purple; fine (l)-grained; well- to moderately-sorted (bimodally-sorted?); sub-rounded; flat-laminated to massive sandstone beds with lamina slightly alternating in grain sizes (up to medium (l) size) with silty and micaceous intervals; bed topped by TROUGH CROSS-BEDDED SANDSTONE and DEFORMED SANDSTONE beds; the remainder of this section is not accessible

CONGLOMERATIC TROUGH CROSS-BEDDED SANDSTONE: tan to yellow; coarse (u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; conglomeratic trough cross-bedded sets (20-40 cm thick); bedding shows concentrations and abundance of pebble-size quartz, feldspars, granitic fragments and mud clasts of different sizes and shapes, appear to be concentrated at bases of sets and foresets (conglomerates to sand ratio is more than 30:70); evolves into (PEBBLY) (THINLY-BEDDED) TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE sets

PEBBLY TROUGH CROSS-BEDDED SANDSTONE: tan to yellow; medium (u)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (20-30 cm thick); beddings shows concentrations of pebble-size quartz, feldspars and granitic fragments (and rare mud clasts) along bases of cycles, sets, and foresets

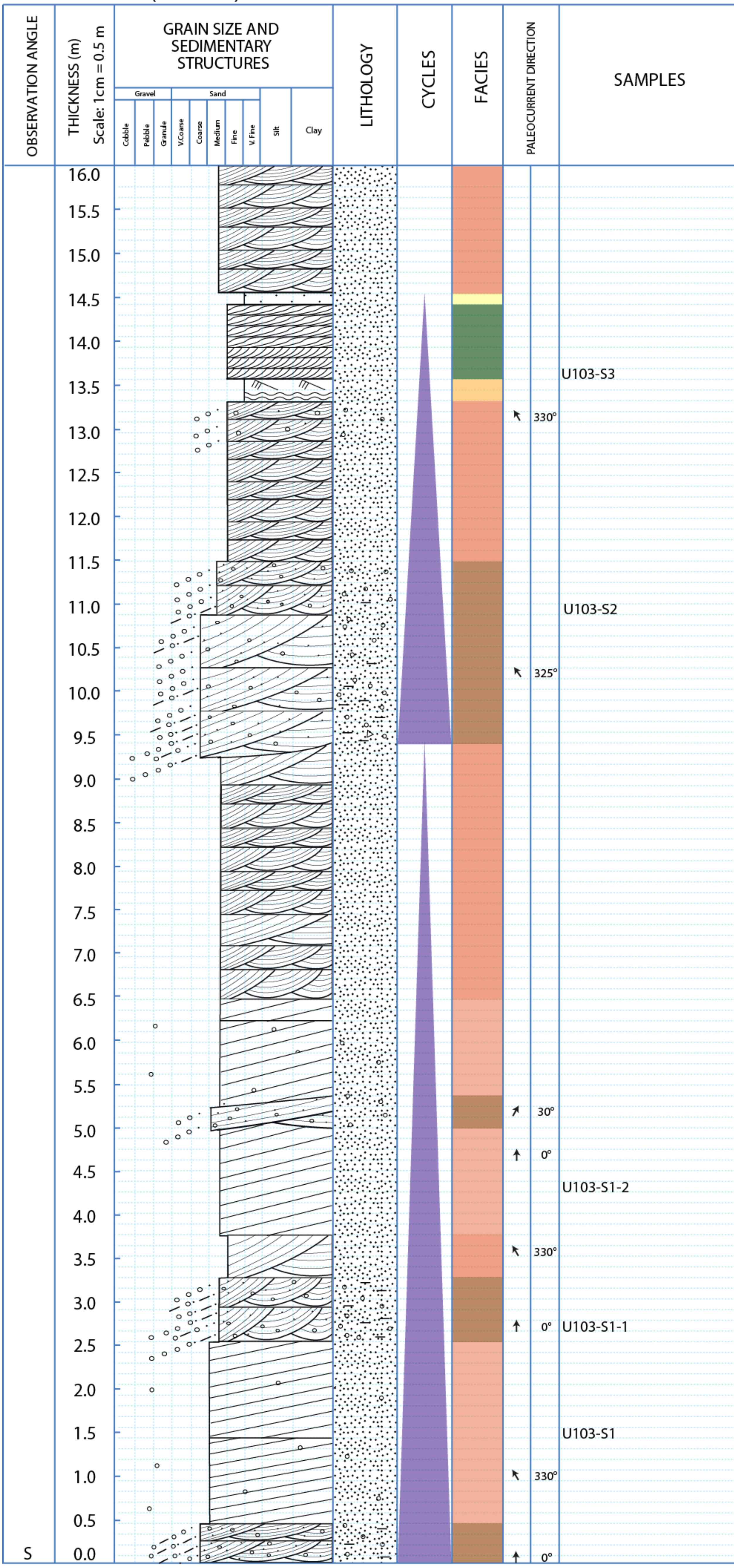
FLAT-LAMINATED SANDSTONE: tan to pink; fine (l and u)-grained; moderately-sorted (bimodally-sorted?); sub-rounded; (alternating bright-dark colors) flat-laminated sandstone beds

CITY/TOWN: Al Ula

SECTION: U103 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 37.468′, E 38° 02.337′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: beige to tan; medium (l)- to coarse (u)-grained; well- to moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (20-75 cm thick); abundant truncations and scourings; inclusions of pebble-size quartz, mud clasts and rare feldspars and granitic fragments; fining-upward trend into fine (l)-grained, WAVY- TO RIPPLE-LAMINATED and MASSIVE SANDSTONE beds; one bed shows THINLY-BEDDED TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE sets (~15 cm thick)

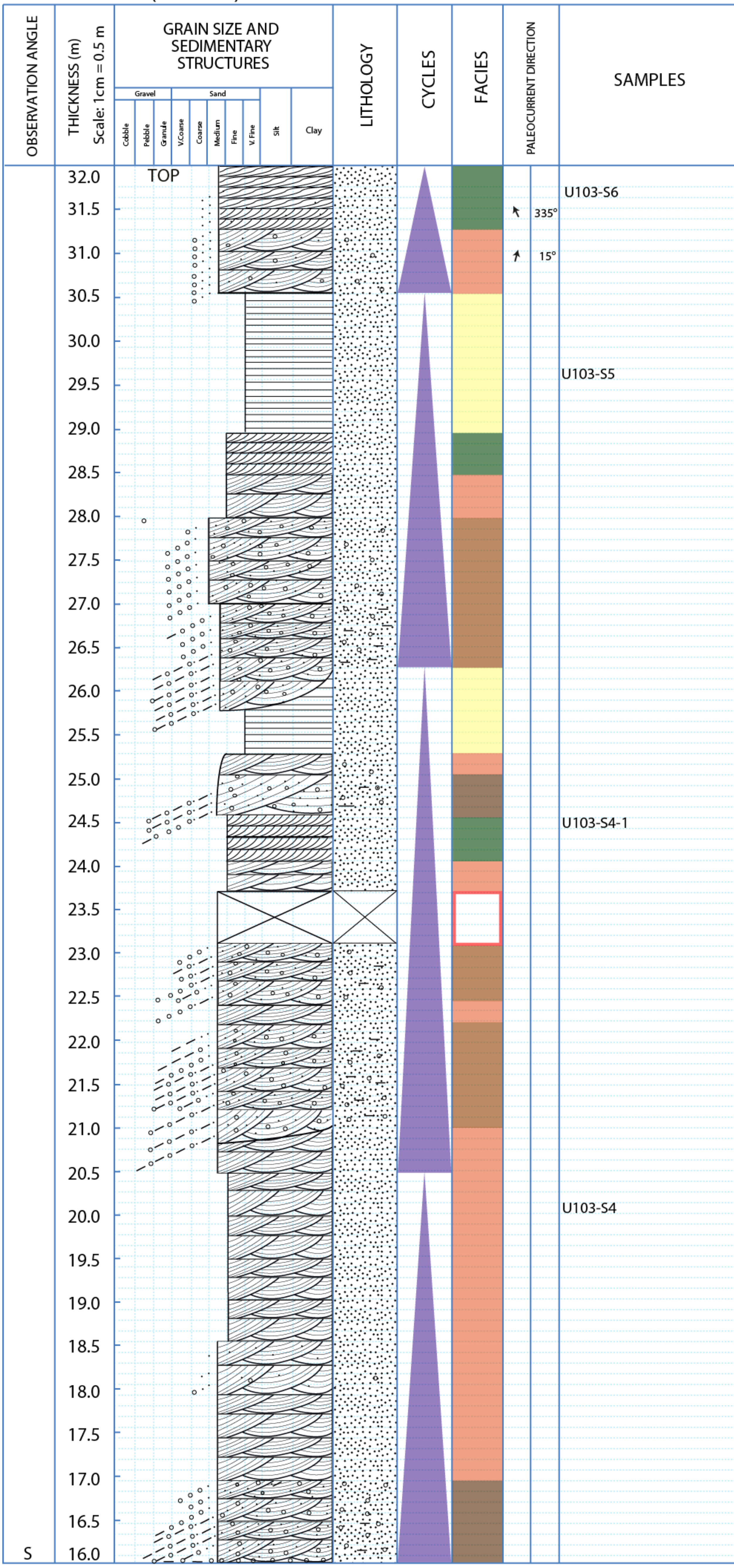
(PEBBLY) TROUGH AND PLANAR TABULAR CROSS-BEDDED SANDSTONE: beige to tan; medium (u)- to coarse (u)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (20-40 cm thick; variable widths) and planar tabular cross-bedded sets (25-100 cm thick); abundant truncations and scouring; fining-upward trend with very angular-grained, very poorly-sorted bases; inclusions of pebble-size quartz and mud clasts; cycle-tops are better sorted with random distribution of pebble-size quartz

CITY/TOWN: Al Ula

SECTION: U103 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 37.468′, E 38° 02.337′



DESCRIPTION / REMARKS

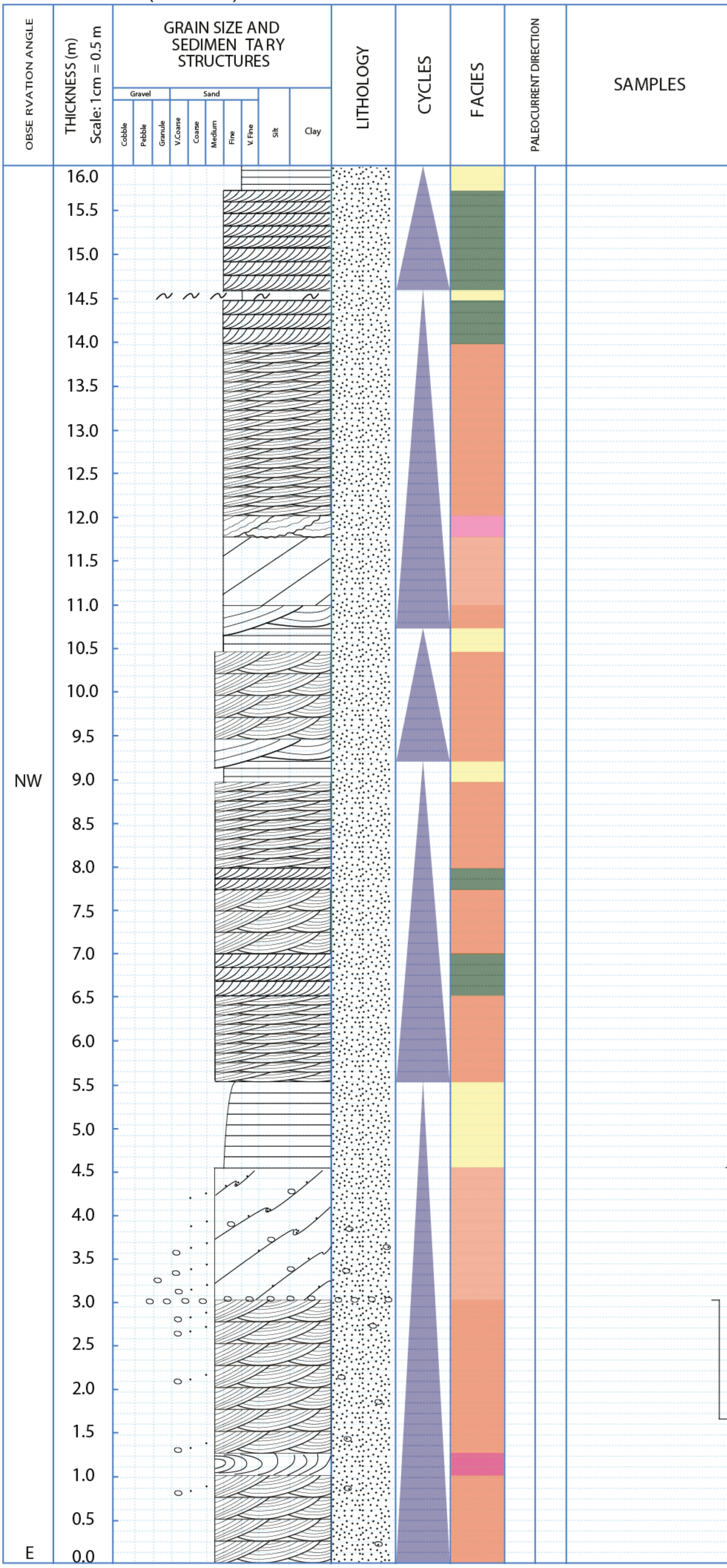
(CONGLOMERATIC) (PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: beige, tan and reddish; medium (l)- to coarse (l)-grained; moderately- to poorly-sorted; sub- to well-rounded; (conglomeratic) (pebbly) trough cross-bedded sets (10-75 cm thick); fining-upward trend with decreasing set-thicknesses; bases of cycles and beds show concentrations of pebble-size quartz (2-5 cm in size) and mud clasts (3 cm in size, up to 20 cm); some beds show scouring and truncations; sequences develop THINLY-BEDDED TANGENTIAL TO SIGMOIDAL CROSS-BEDDED and FLAT-LAMINATED SANDSTONE beds

CITY/TOWN: Al Ula (Mada'in Saleh - Al Khuraimat)

SECTION: U201 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 46.934',E 37' 56.759'



DESCRIPTION / REMARKS

CROSS-BEDDED SANDSTONE: white to tan (weathering); medium (l)-grained; well- to moderately-sorted; sub-rounded to rounded; sets include TROUGH CROSS-BEDDED SANDSTONE sets (<10-15 cm thick), THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE sets (<10 cm thick) and one PLANAR TABULAR CROSS-BEDDED SANDSTONE set (up to 70 cm thick); fining-upward trend, locally developing into maroon, fine (l)-grained FLAT-LAMINATED TO MASSIVE SANDSTONE beds; one massive sandstone bed displays horizontal trace fossils; DEFORMED SANDSTONE bed is observed within succession

TROUGH TO THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); medium (u)-grained; moderately- to poorly-sorted; sub-rounded to rounded; trough cross-bedded sets (10-15 cm thick) and thinly-bedded tangential cross-bedded sets (<10 cm thick); minor concentrations of coarser-sand grains at bases of foresets; fining-upward trend, locally developing into FLAT-LAMINATED SANDSTONE beds, which are truncated by overlaying bedding

FLAT-LAMINATED SANDSTONE: buff white, variegated (weathering); fine (u)- to medium (l)-grained; well- to moderately-sorted; sub- to well-rounded; flat-laminated sandstone beds; fining-upward into maroon, silty- to fine (l)-grained top

PLANAR TABULAR CROSS-BEDDED SANDSTONE: buff white, tan to orange (weathering); medium (u)-grained; moderately-sorted; sub-rounded to rounded; planar tabular cross-bedded set (up to 100 cm thick); rare concentrations of pebble-size quartz at bases of foresets; evidence of soft-sediment deformation at bases of foresets; lag shows concentrations of pebble-size quartz (up to 4 cm in size)

TROUGH CROSS-BEDDED SANDSTONE: buff white, tan to orange (weathering); medium (u)-grained; moderately-sorted; sub- to rounded; trough cross-bedded sets (15-20 cm thick); rare concentrations of pebble-size quartz at bases of foresets; bedding shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS bed

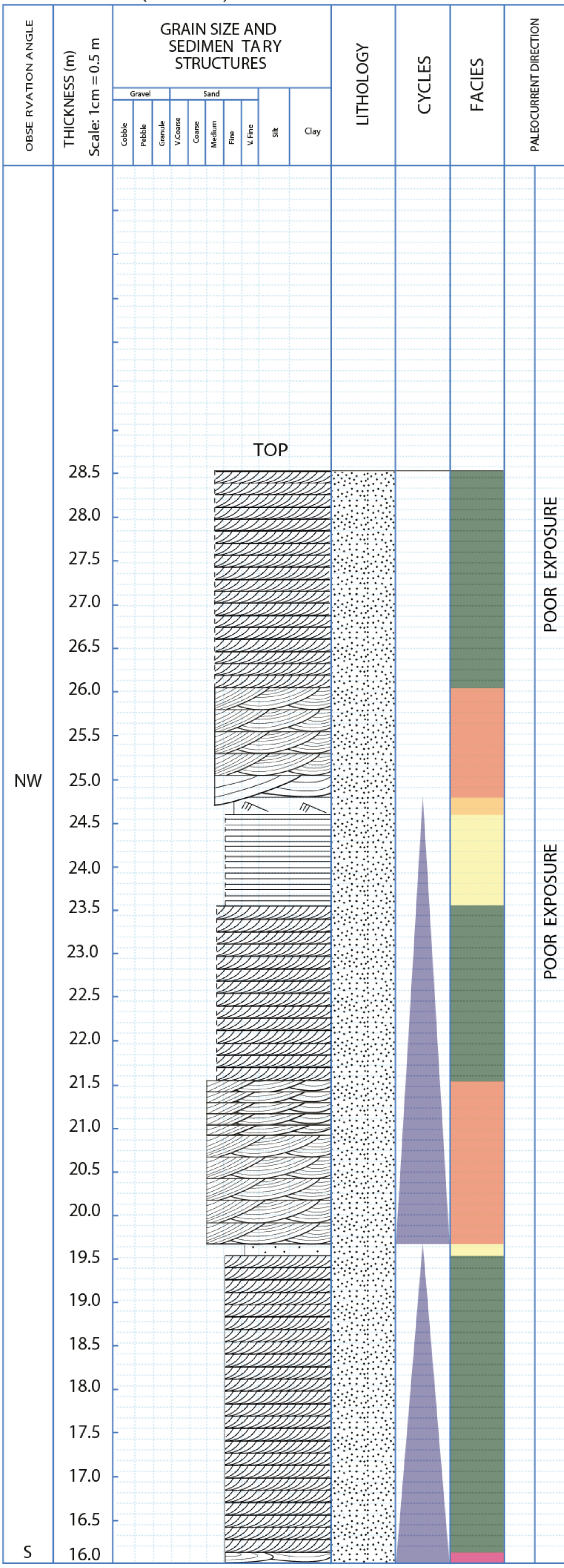
CITY/TOWN: Al Ula (Mada'in Saleh - Al Khuraimat)

PAGE 2 OF 2

SECTION: U201 (2 PAGES)

NAME: ABDULLAH WAHBI

LOC ATION: N 26° 46.934',E 37' 56.759'



SAMPLES

DESCRIPTION / REMARKS

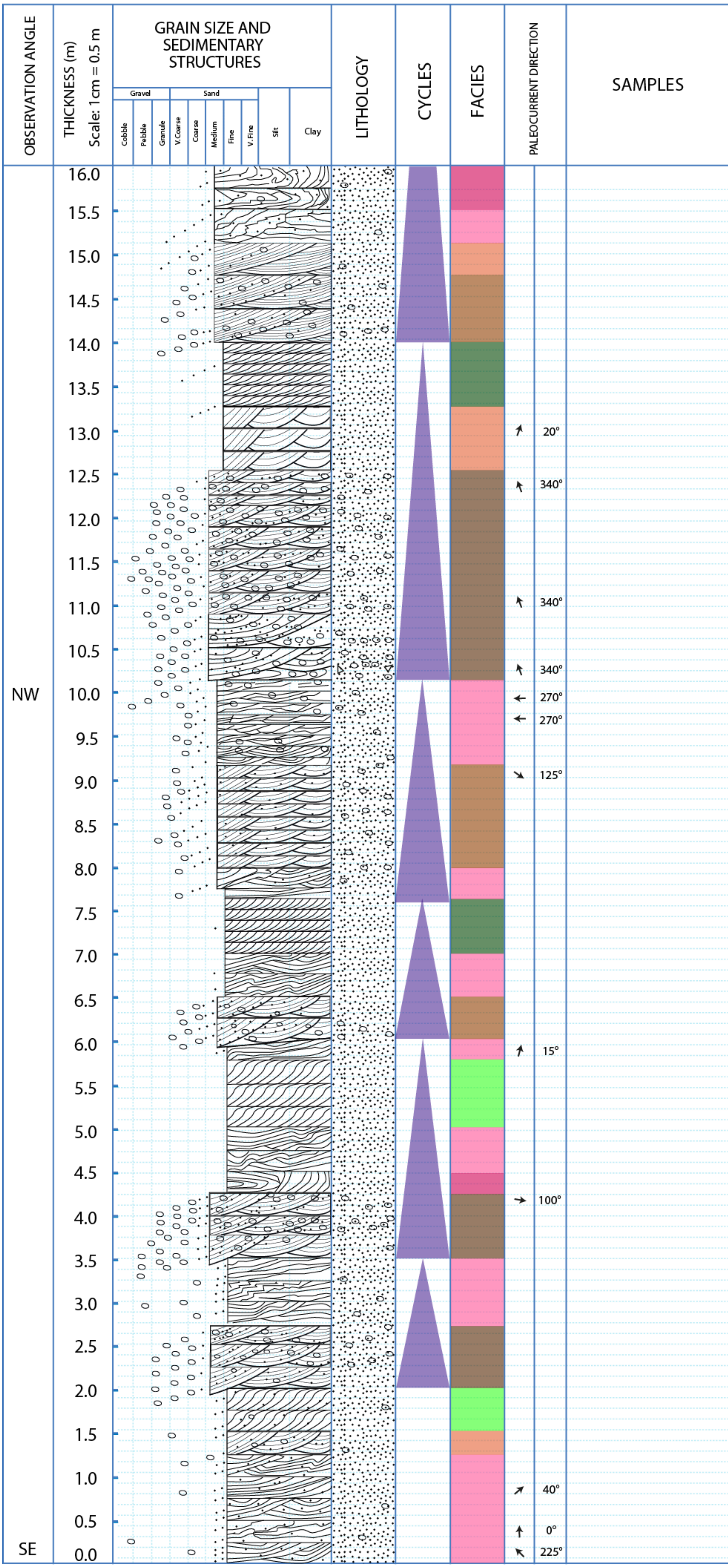
TROUGH AND THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE: white, tan to beige (weathering); medium (l)- to coarse (l)-grained; well- to moderately-sorted; sub- to well-rounded; trough cross-bedded sets (<10-20 cm thick) and thinly-bedded tangential cross-bedded sets (<10 cm thick); fining-upward trend into white to dark-purple, fine (u)- to medium (l)-grained micaceous RIPPLE- TO FLAT-LAMINATED AND MASSIVE SANDSTONE beds; bedding show CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS (at 16.0 m); poor-exposure in places (man-made modifications – tomb sculpturers!)

CITY/TOWN: Al Ula (Mada'in Saleh - Ad Diwan)

SECTION: U202a (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.571', E 37° 57.739'



DESCRIPTION / REMARKS

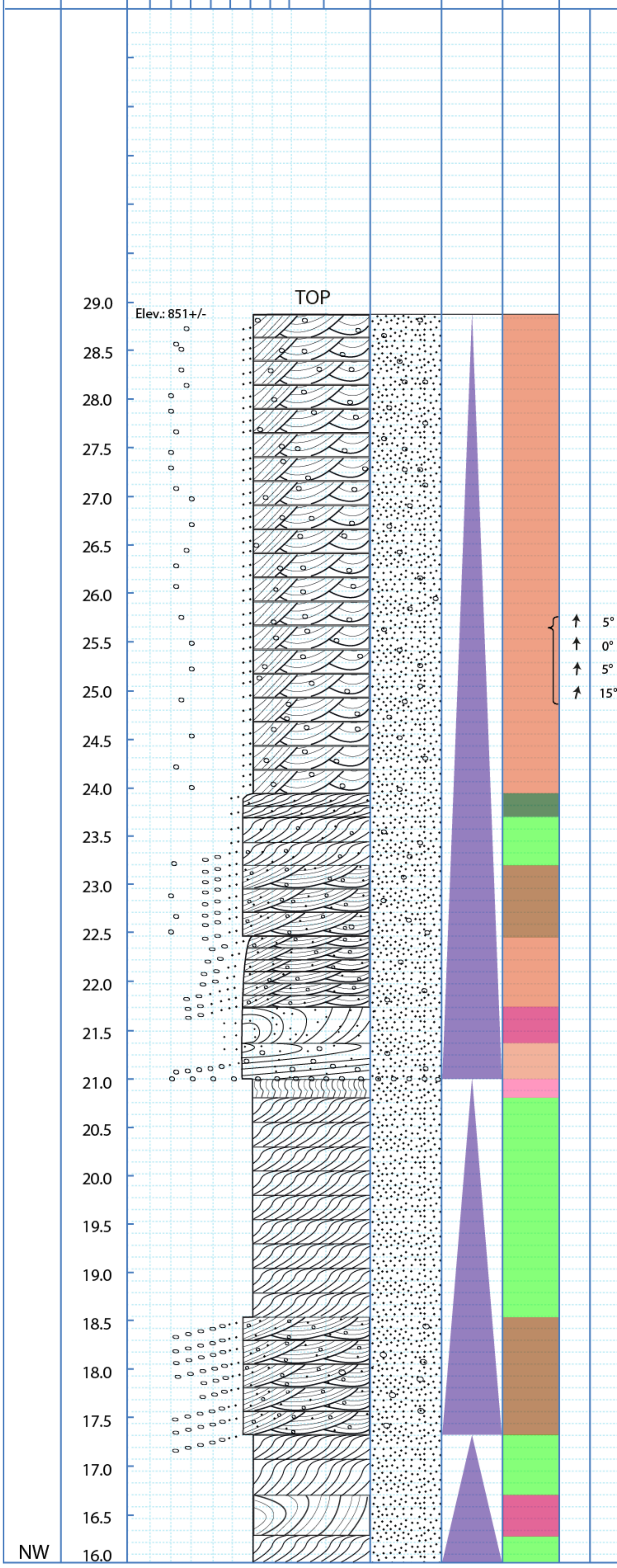
(CONGLOMERATIC) (PEBBLY) TROUGH AND (THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED SANDSTONE: white, tan to beige weathering; medium (l)- to coarse (l)-grained; well- to moderately-sorted; sub- to well-rounded; cycles contain (conglomeratic) (pebbly) trough cross-bedded sets which develop into (thinly-bedded) sigmoidal cross-bedded sets (<10-25 cm thick); fining-upward trend with coarse-grained and very poorly-sorted bed bases; bedding shows significant concentrations of pebble-size quartz (angular, elongated and well-rounded) and some feldspars and granitic fragments (found well-rounded and angular; up to 4 cm in size) concentrated at bases of beds and sets; bedding shows DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

(CONGLOMERATIC) (PEBBLY) TROUGH AND TANGENTIAL CROSS-BEDDED SANDSTONE: white, tan weathering, coarse (l)- to medium (l)-grained; moderately- to well-sorted; sub- to well-rounded; cycles contain (conglomeratic) (pebbly) trough cross-bedded sets which develop into (thinly-bedded) tangential cross-bedded sets (<10-25 cm thick); fining-upward trend with coarser-grained, poorly-sorted bases showing significant concentrations of pebble-size quartz (up to 4 cm; angular, elongated and well-rounded quartz); bedding contains DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

CITY/TOWN: Al Ula (Mada'in Saleh - Ad Diwan)

SECTION: U202a (2 PAGES) NAME: ABDULLAH WAHBI LOCATION: N 26° 47.571', E 37° 57.739'

OBSERVATION ANGLE	THICKNESS (m) Scale: 1 cm = 0.5 m	GRAIN SIZE AND SEDIMENTARY STRUCTURES (Gravel: Cobble, Pebble, Granule; Sand: V.Coarse, Coarse, Medium, Fine, V.Fine; Silt; Clay)	LITHOLOGY	CYCLES	FACIES	PALEOCURRENT DIRECTION	SAMPLES	DESCRIPTION / REMARKS



NOTE: The top of this measured section is reached; succession continues in U202b, which can be seen from this top. Elevation noted using a GPS. U202a and U202b are two composite sections in Ad Diwan.

CROSS-BEDDED SANDSTONE: white, beige weathering; medium (l and u)-grained; moderately-sorted; sub-angular to rounded; cross-bedded sets (<10-40 cm thick) include (PEBBLY) PLANAR TABULAR CROSS-BEDDED, (PEBBLY) TROUGH CROSS-BEDDED, and (THINLY-BEDDED) TANGENTIAL TO SIGMOIDAL CROSS-BEDDED sets; various concentrations of sand- to pebble-size quartz; fining-upward trend; lags show concentrations of pebble-size we-rounded quartz; bedding includes DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

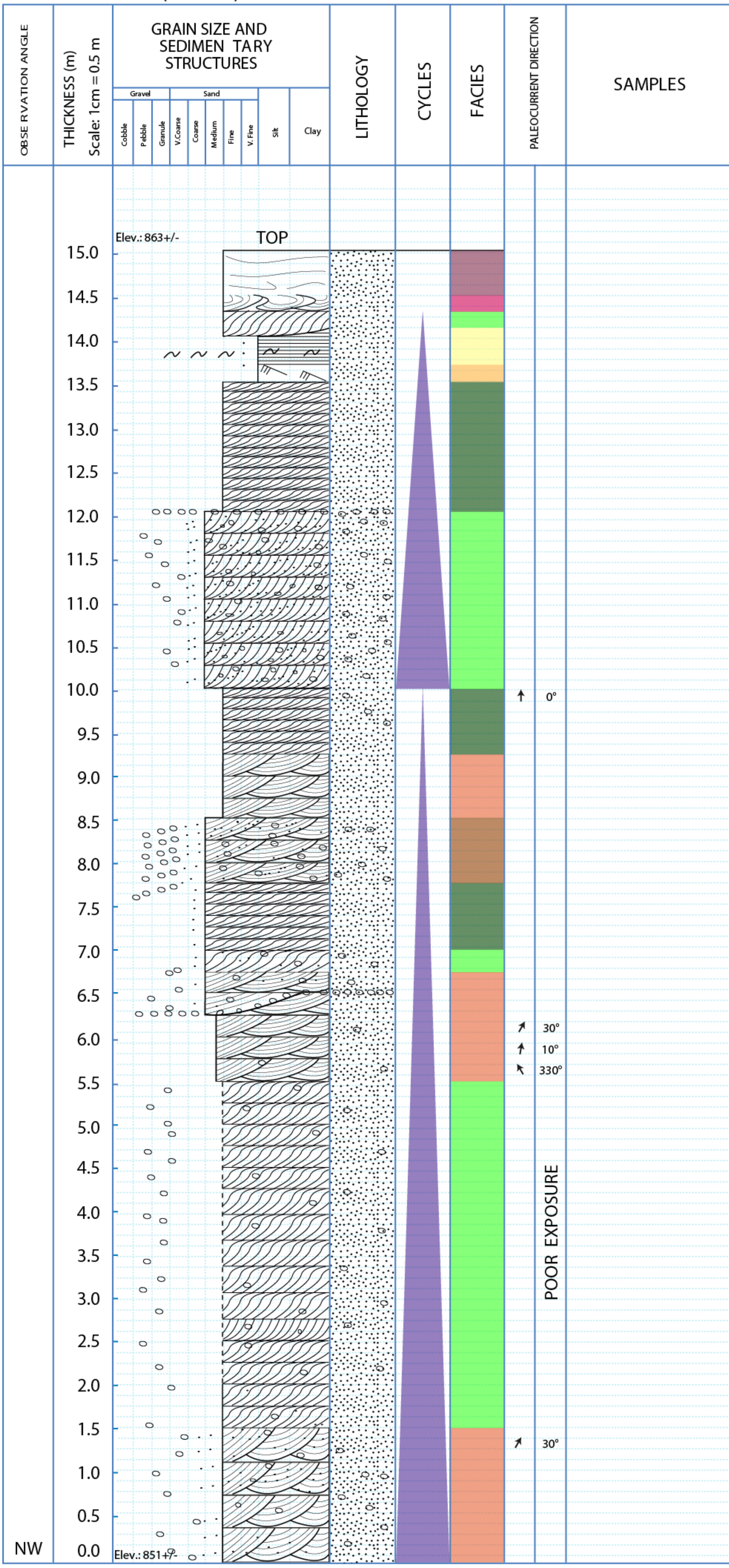
PEBBLY TROUGH AND SIGMOIDAL CROSS-BEDDED SANDSTONE: white, beige weathering; medium (l and u)-grained; moderately-sorted; sub-angular to rounded; cycle starts with pebbly trough cross-bedded sets (with concentrations of sand- to pebble-size quartz), developed into sigmoidal cross-bedded sets (10-30 cm thick); fining-upward trend; bedding includes DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds; uppermost sets is intensively deformed by overlain set deposition (at ~21.0 m)

CITY/TOWN: Al Ula (Mada'in Saleh - Ad Diwan)

SECTION: U202b (1 PAGE)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.380', E 37° 57.950'



DESCRIPTION / REMARKS

CROSS-BEDDED SANDSTONE: white, buff, tan weathering; medium (l)- to coarse (l)-grained; well- to moderately-sorted; sub- to well-rounded; bedding includes (PEBBLY) TROUGH CROSS-BEDDED and (PEBBLY) (THINLY-BEDDED) TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE sets (<10-25 cm thick); pebbles concentrated at bases of sets and foresets in places; succession fines-upward into RIPPLE-LAMINATED SANDSTONE and FLAT-LAMINATED SANDSTONE beds which display evidence of horizontal trace fossils (at ~14.0 m); lags show concentrations of pebble-size rounded quartz; uppermost beds show DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS

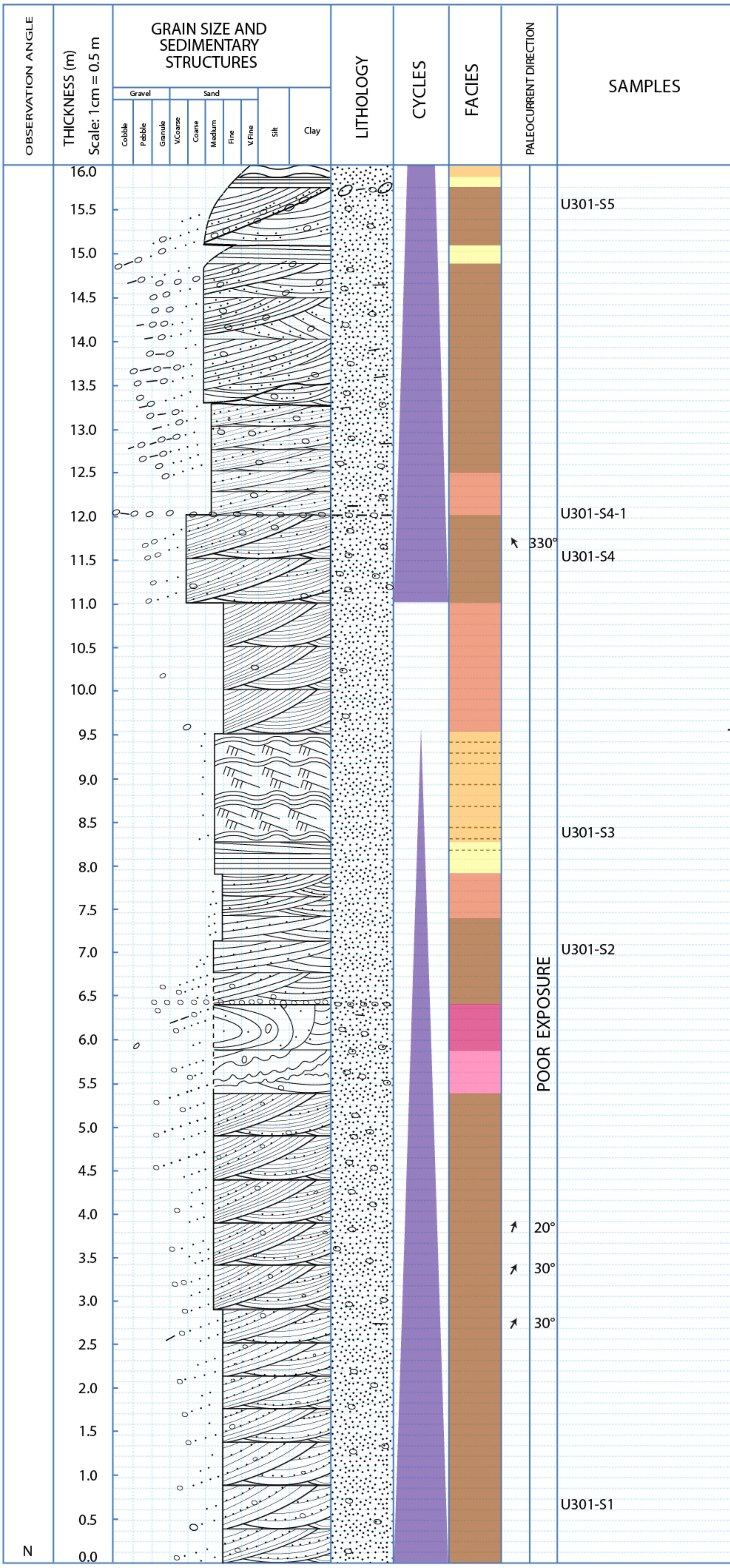
CITY/TOWN: Al Ula

PAGE 1 OF 2

SECTION: U301 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 39.961′, E 37° 55.345′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: reddish brown; medium (l)- to coarse (l)-grained; moderately- to poorly-sorted; angular to sub-rounded; (pebbly) trough cross-bedded sets vary in thicknesses and widths; sets show pebble-size quartz, feldspars, mud clasts, sandstone clasts and granitic fragments (up to <5 cm in size), randomly distributed and concentrated at bases of sets and foresets; abundant truncations and scouring; recurring lags with concentrations of pebble-size quartz, mud clasts and sandstone clasts; fining-upward cycles to very fine (u)-grained, WAVY- TO LENTICULAR-LAMINATED and FLAT-LAMINATED SANDSTONE

WAVY-, RIPPLE- (LENTICULAR-), AND LOW-ANGLE TO FLAT-LAMINATED SANDSTONE: reddish brown; medium (u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; generally wavy- to flat- and rarely discontinuous lenticular-laminated sandstone beds; some laminations show low-angle cross-bedding; beds contains lamina of coarser-grain sizes

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE; reddish brown, medium (l and u)-grained, moderately- to poorly-sorted, sub-angular to sub-rounded; (pebbly) trough cross-bedded sets (30-40 cm thick); some beds are narrow while others could reach up to 7 m in width; coarse-sand grains and some pebbles are randomly distributed or concentrated at bases of sets and foresets (quartz, rare mud clasts; 2 cm in size); one lag observed with pebbles (< 1 cm in size); DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within the sequence

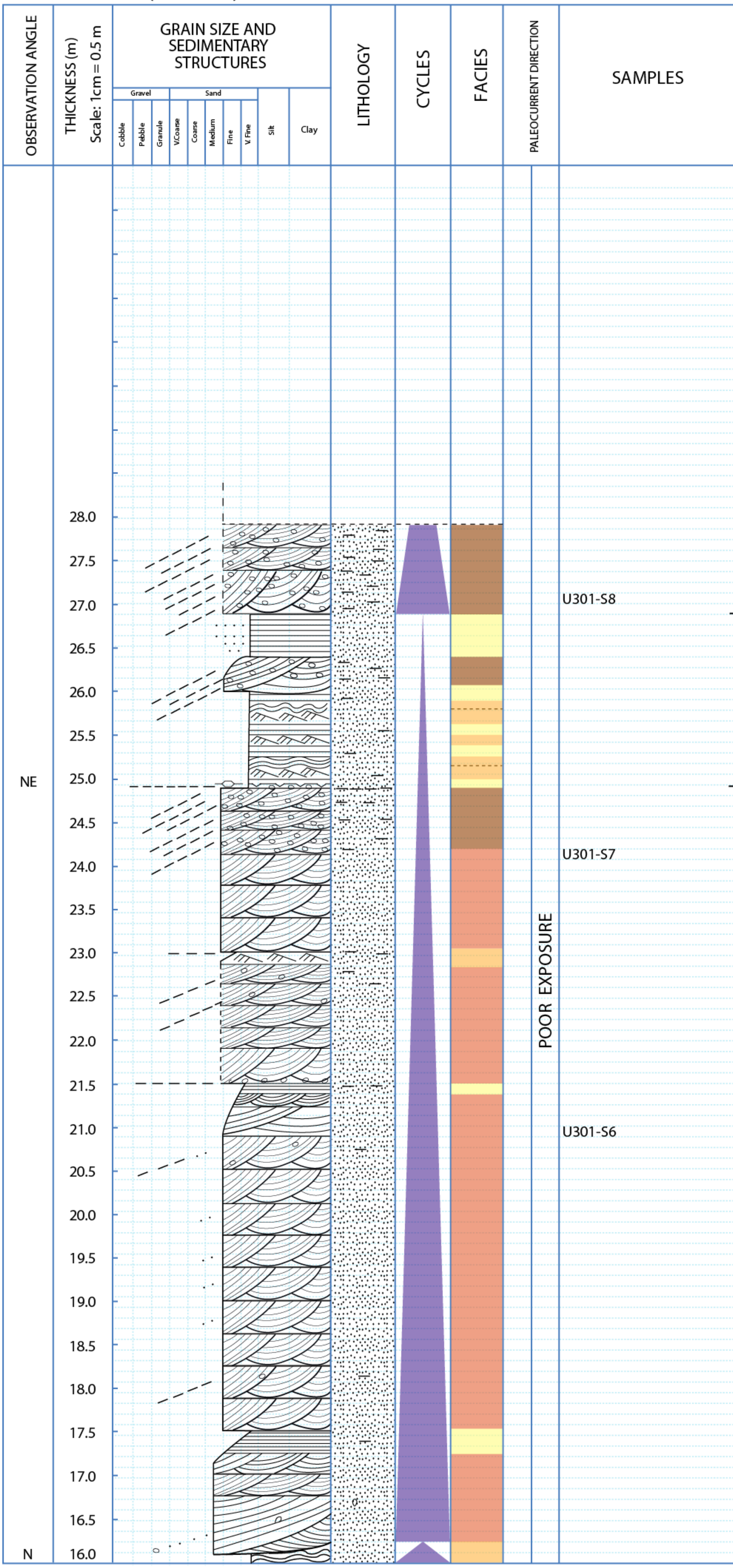
CITY/TOWN: Al Ula

PAGE 2 OF 2

SECTION: U301 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 39.961′, E 37° 55.345′



DESCRIPTION / REMARKS

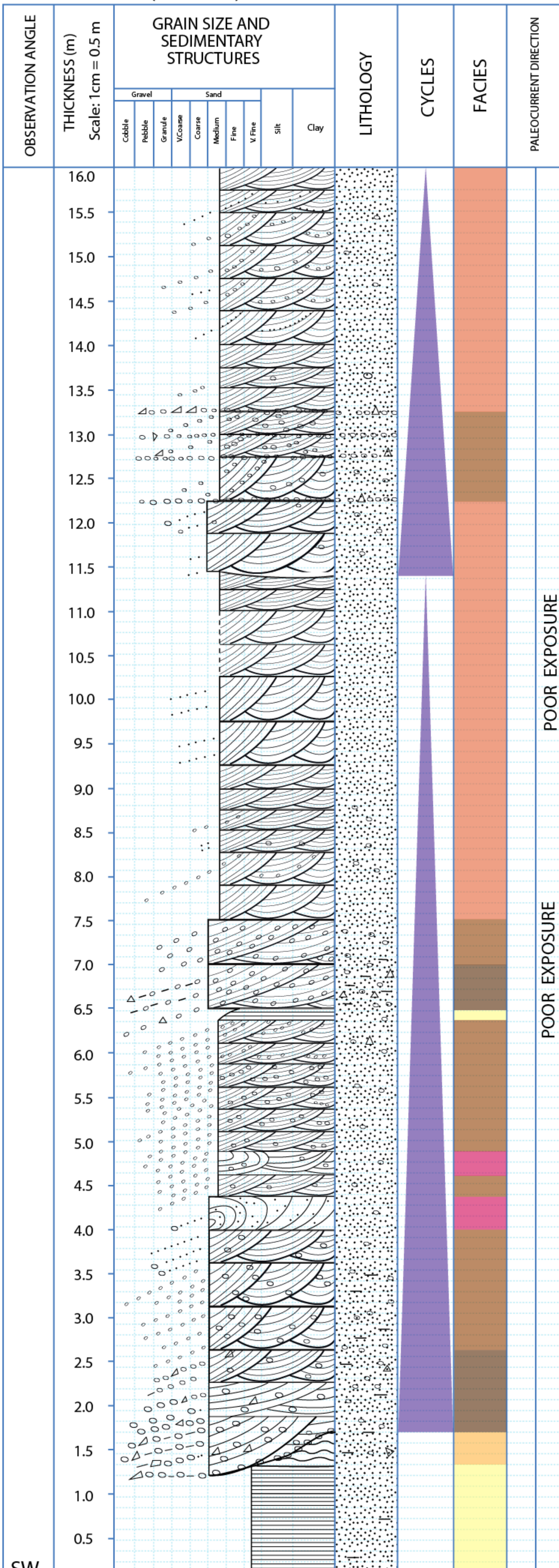
PEBBLY TROUGH CROSS-BEDDED SANDSTONE: reddish brown; medium (l)-grained; moderately-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-30 cm thick); narrow beds (<4 m in width); inclusions of mud clasts (up to 5 cm in size) along bases of sets and foresets

WAVY-, RIPPLE- AND FLAT-LAMINATED SANDSTONE: maroon- to reddish-brown; very fine (u)-grained; well- to moderately-sorted; sub-angular to sub-rounded; wavy-, ripple- and flat-laminated, with minor discontinuous lenticular-laminated sandstone beds; evidence of desiccation and presence of mud cracks; includes one medium (l)-grained, PEBBLY TROUGH CROSS-BEDDED SANDSTONE bed, which is heavily concentrated with mud clasts (up to 10 cm in size)

TROUGH CROSS-BEDDED SANDSTONE: reddish brown; medium (l and u)- grained; moderately-sorted; sub-angular to sub-rounded, trough cross-bedded sets (10-30 cm thick); sets are up to 4 m in width; minor sand- to pebble-size quartz inclusions and significant quantity of mud clasts randomly distributed and concentrated at bases of sets and foresets (up to 10 cm); recurring lags show concentrations of pebble-size mud clasts; fining-upward cycles into very fine (u)-grained, silty WAVY- TO RIPPLE-LAMINATED and FLAT-LAMINATED SANDSTONE beds

CITY/TOWN: Al Ula

SECTION: U302 (3 PAGES) NAME: ABDULLAH WAHBI LOCATION: N 26° 40.195′, E 37° 56.238′



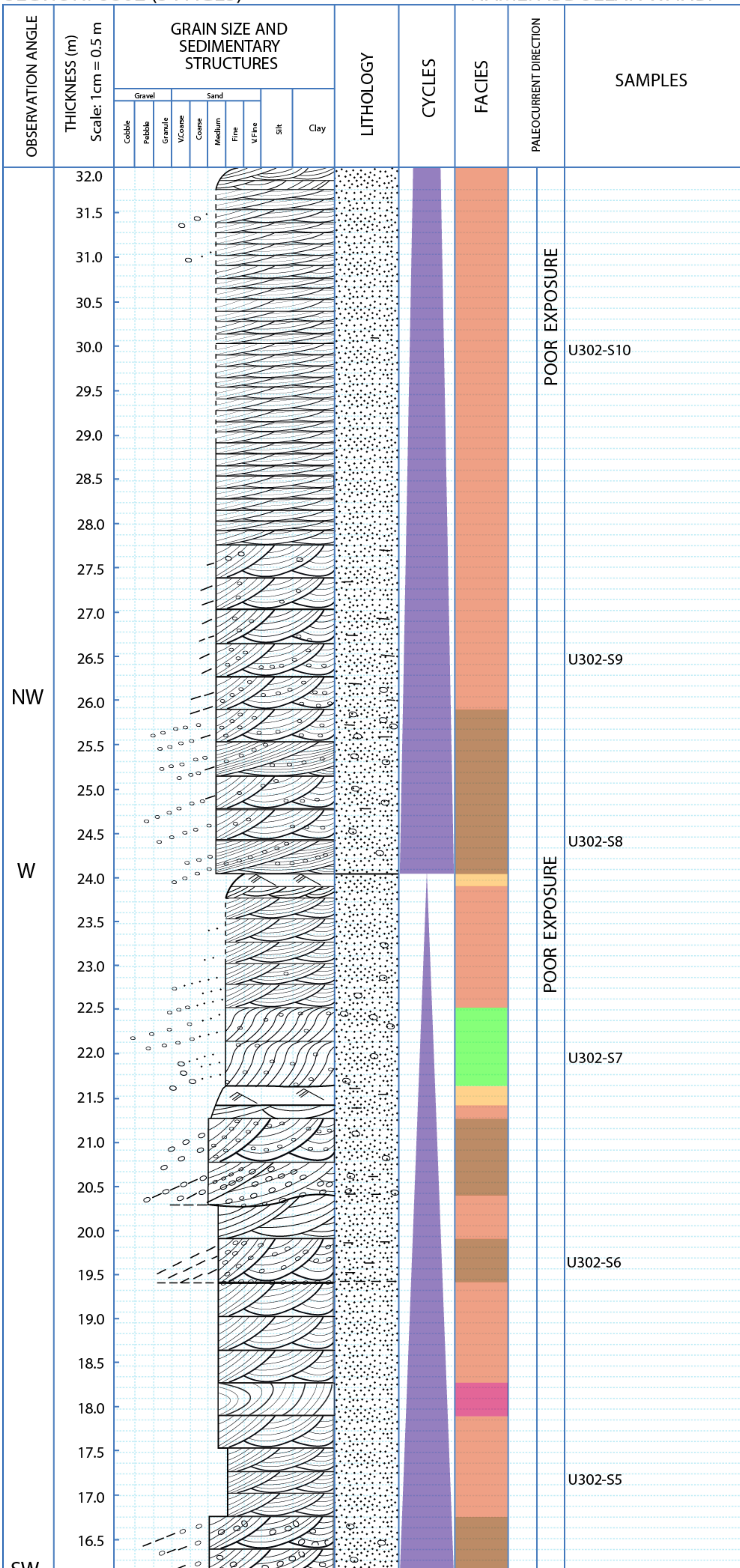
SAMPLES	DESCRIPTION / REMARKS
	(CONGLOMERATIC) (PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish-brown; medium (u)- to coarse (l)-grained; well- to moderately-sorted; sub-angular to rounded; (conglomeratic) (pebbly) trough cross-bedded sets (10-40 cm thick; <5 m in width); concentrations of pebble-size quartz, granitic fragments and rare mud clasts (<10 cm in size) found at bases of sets and foresets; fining-upward trend; evidence of scouring; lags show concentrations of pebble-size quartz and granitic fragments (up to 5cm in size)
U302-S4	
U302-S3	
U302-S2	(CONGLOMERATIC) (PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish-brown; medium (u)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; (conglomeratic) (pebbly) trough cross-bedded sets (10-50 cm thick); show significant concentrations of pebble-size quartz and minor granitic fragments and mud clasts (up to 10 cm in size) at bases of sets and foresets; fining-upward trend into FLAT-LAMINATED to MASSIVE SANDSTONE beds; lag shows concentration of pebble-size quartz, granitic fragments and mud clasts (up to 10 cm in size); variable cementation
U302-S1	FLAT-LAMINATED SANDSTONE: purple to tan; very fine (u)- to medium (l)-grained; moderately- to well-sorted; sub-rounded to rounded; flat-laminated sandstone bed; topped by WAVY-LAMINATED SANDSTONE bed

CITY/TOWN: Al Ula

SECTION: U302 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 40.195', E 37° 56.238'



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (u)-grained; moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (<10-30 cm thick); bases of sets and foresets show concentrations of pebbles (up to 3 cm in size) of rounded quartz and mud clasts

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to reddish-brown; medium (l)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to rounded; (pebbly) trough cross-bedded sets (10-50 cm thick; variable widths); bedding shows concentrations of pebble-size quartz with subordinate mud clasts found at bases of sets and foresets; bedding develops two sets of PEBBLY SIGMOIDAL CROSS-BEDDED SANDSTONE; one bed shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS; fining-upward trend into maroon-purple-colored, fine (l)-grained, micaceous LENTICULAR- TO RIPPLE-LAMINATED SANDSTONE beds; scouring and erosional surfaces observed; lags show concentrations of pebble-size mud clasts

CITY/TOWN: Al Ula

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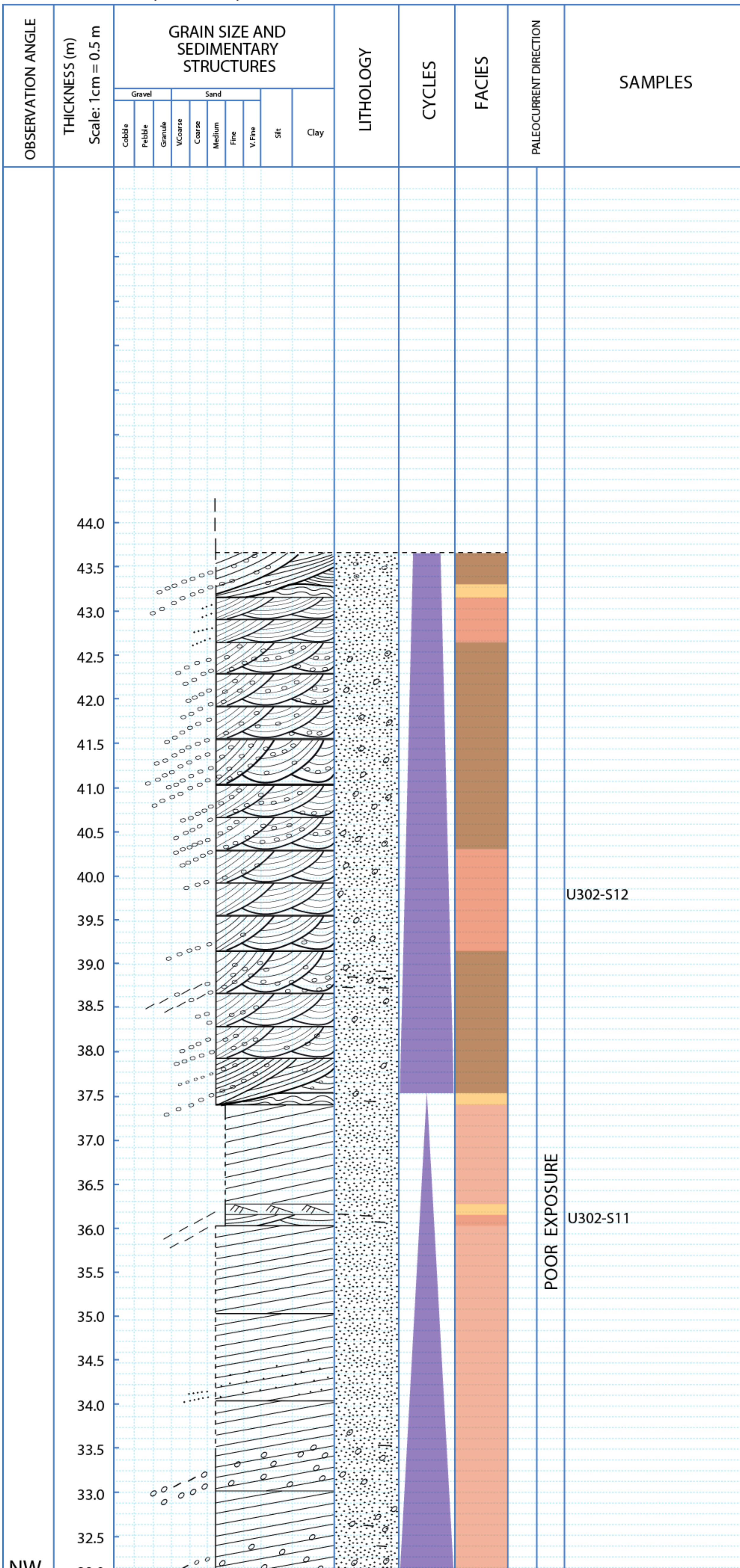
SECTION: U302 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 40.195′, E 37° 56.238′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED AND PLANAR TABULAR CROSS-BEDDED SANDSTONE: tan, medium (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; bedding includes (pebbly) trough cross-bedded sets (20-50 cm thick) and planar tabular cross-bedded sets (100-150 cm thick); quartz and mud clast (rare feldspars) pebbles are found concentrated at bases of sets and foresets (up to 4 cm in size); cycles fine-upward into maroon, fine (l)-grained, silty, discontinuous LENTICULAR- and WAVY- TO RIPPLE-LAMINATED SANDSTONE beds

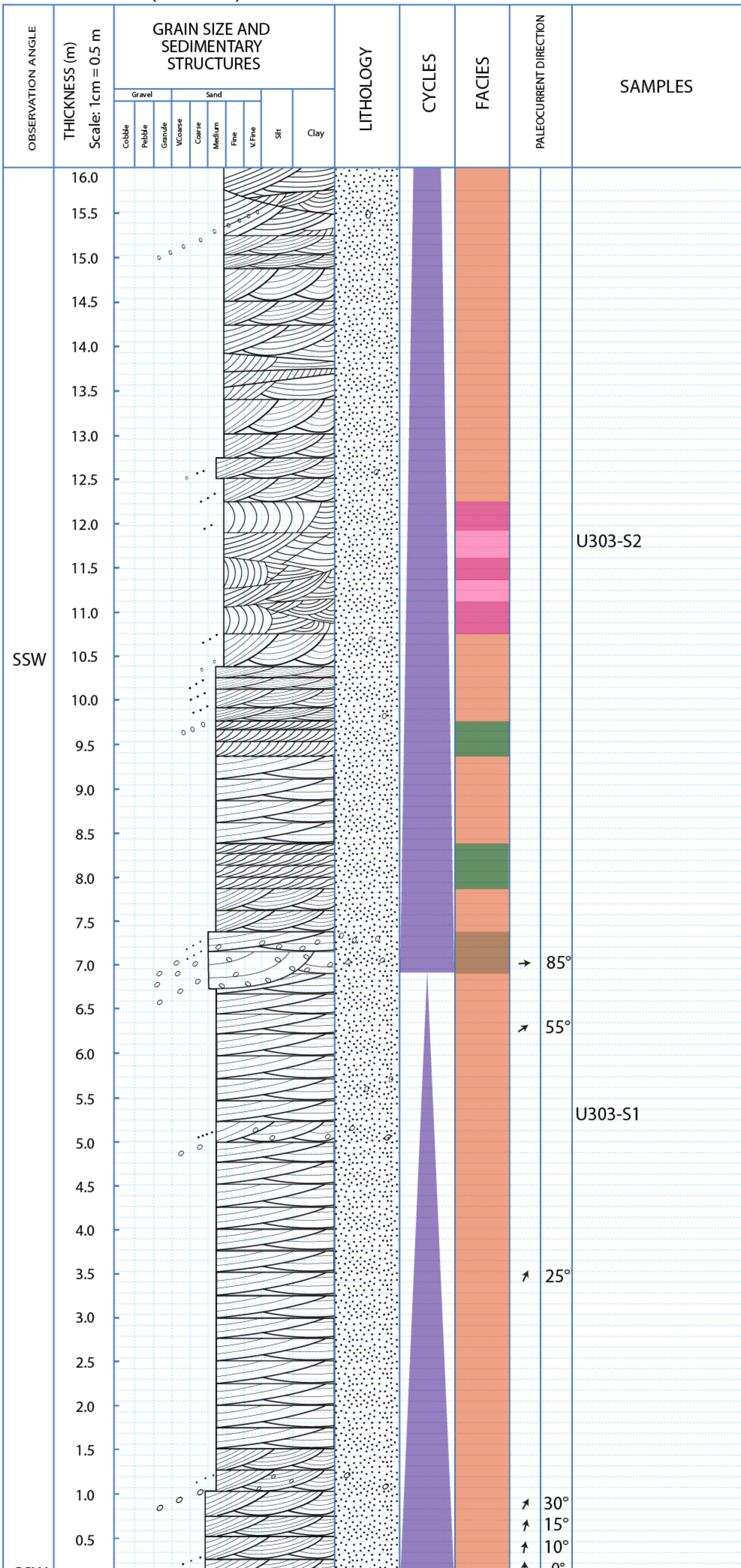
CITY/TOWN: Al Ula

PAGE 1 OF 2

SECTION: U303 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 43.313′, E 37° 58.679′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (<10-30 cm thick); abundance of scouring and truncations; minor inclusions of sand- to pebble-size quartz (up to 2 cm in size); sequences show both DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

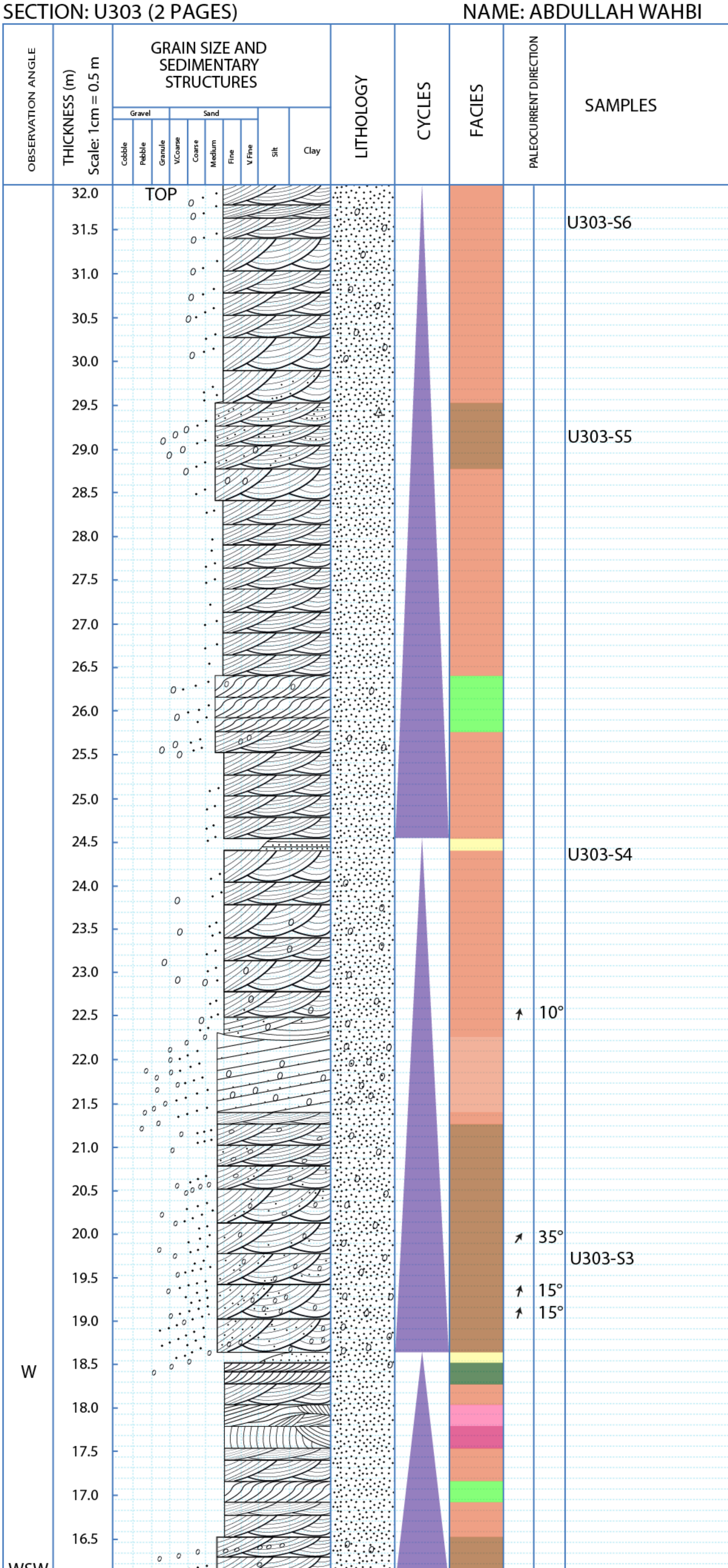
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to brown; medium (l)- coarse(l)-grained; moderately- to poorly-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (10-30 cm thick; 5-10 m width); fining-upward trends; minor inclusions of sand- to pebble-size, well-rounded to rounded quartz; some sets develop THINLY-BEDDED TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE sets

CITY/TOWN: Al Ula

SECTION: U303 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 43.313′, E 37° 58.679′



DESCRIPTION / REMARKS

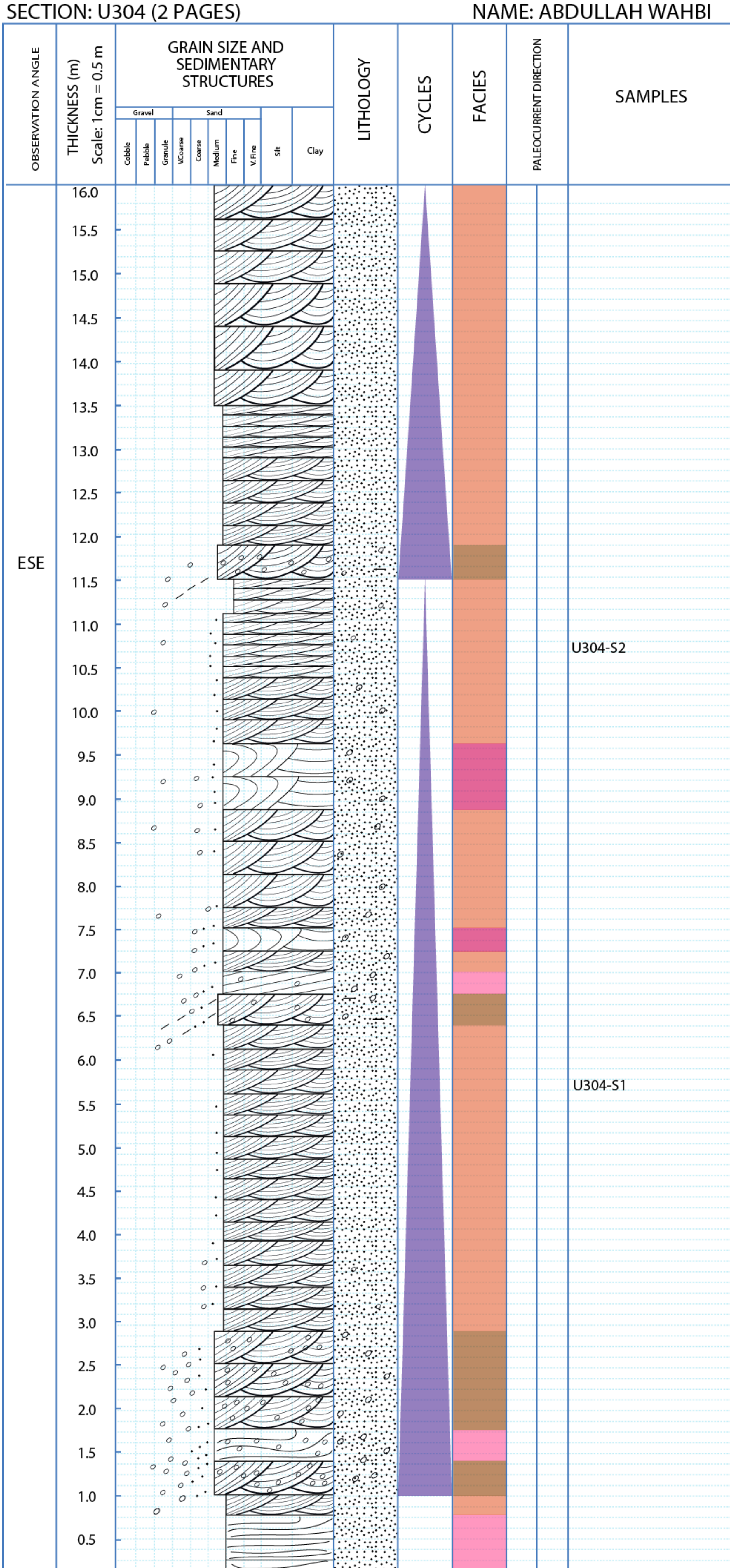
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; moderately- to poorly-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (10-30 cm thick); includes concentrations of pebble-size quartz, some feldspars and rare granitic fragments; some sets develop SIGMOIDAL CROSS-BEDDED SANDSTONE

CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; moderately- to poorly-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (10-20 cm thick; variable thicknesses) and planar tabular cross-bedded set (100 cm thick); bedding shows concentrations of sand- to pebble-size, well-rounded quartz (up to 4 cm in planar tabular cross-bedded set); fining-upward trend into maroon to purple, fine (l)-grained FLAT-LAMINATED TO MASSIVE SANDSTONE beds

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (<10-20 cm thick; variable widths); abundance of truncations and scouring; minor inclusions of sand- to pebble-size quartz (up to 2 cm in size); fining-upward trend into (THINLY-BEDDED) TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE sets and maroon to purple, fine (l)-grained MASSIVE SANDSTONE beds; some beds show DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS

CITY/TOWN: Al Ula

SECTION: U304 (2 PAGES) NAME: ABDULLAH WAHBI LOCATION: N 26° 44.186', E 37° 59.022'



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; fine (u)- to medium (u)-grained; moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (<10-50 cm thick); fining-upward trend; basal sets show sand- to pebble-size quartz and mud clasts (rare granitic fragments) concentrated at bases of foresets; recurring erosive bases; DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within bedding

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; moderately- to poorly-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (10-30 cm thick); fining-upward trend; sand- to pebble-size quartz (2-8 cm in size; mostly well-rounded) concentrated at bases of foresets; some beds shows DEFORMED SANDSTONE

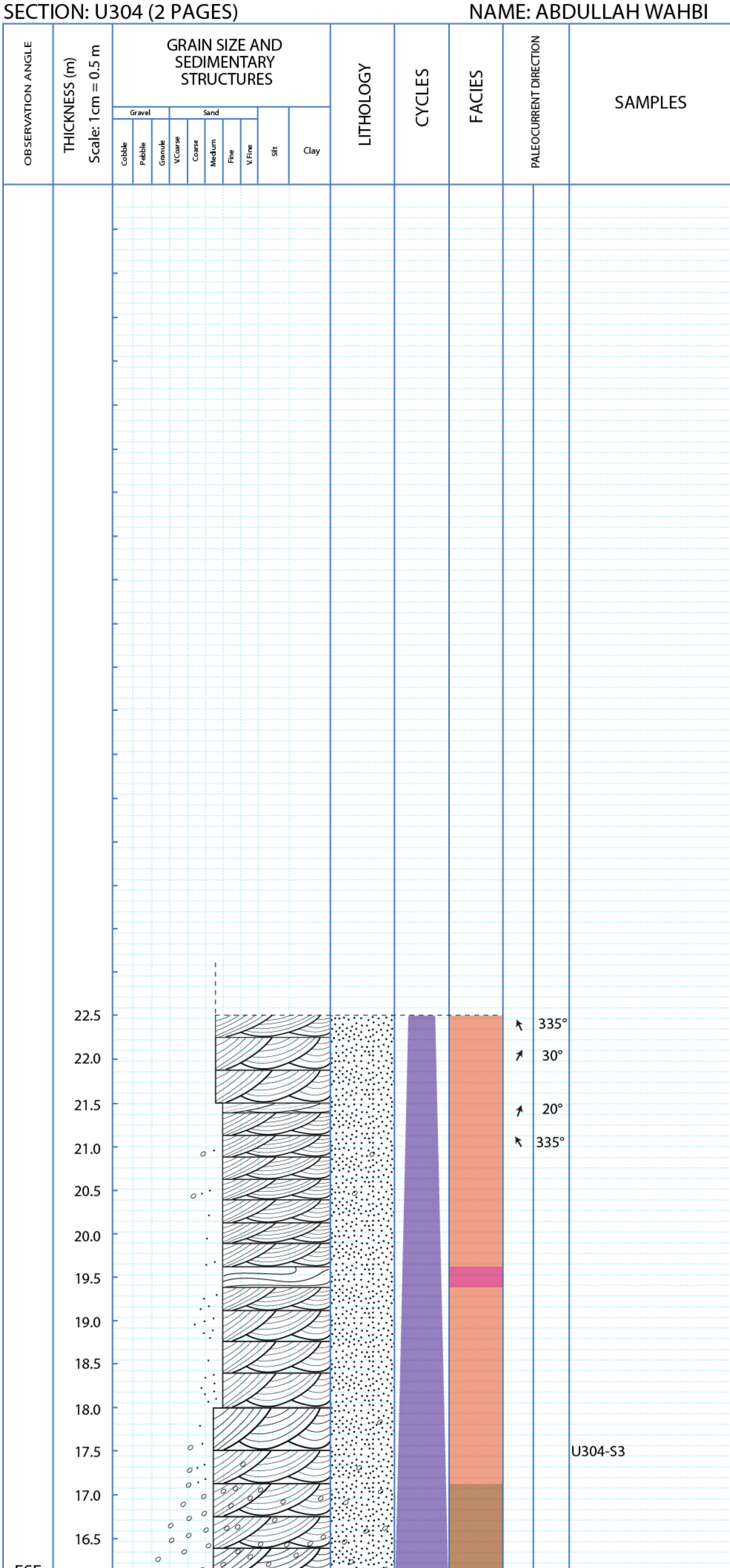
CITY/TOWN: Al Ula

PAGE 2 OF 2

SECTION: U304 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 44.186′, E 37° 59.022′

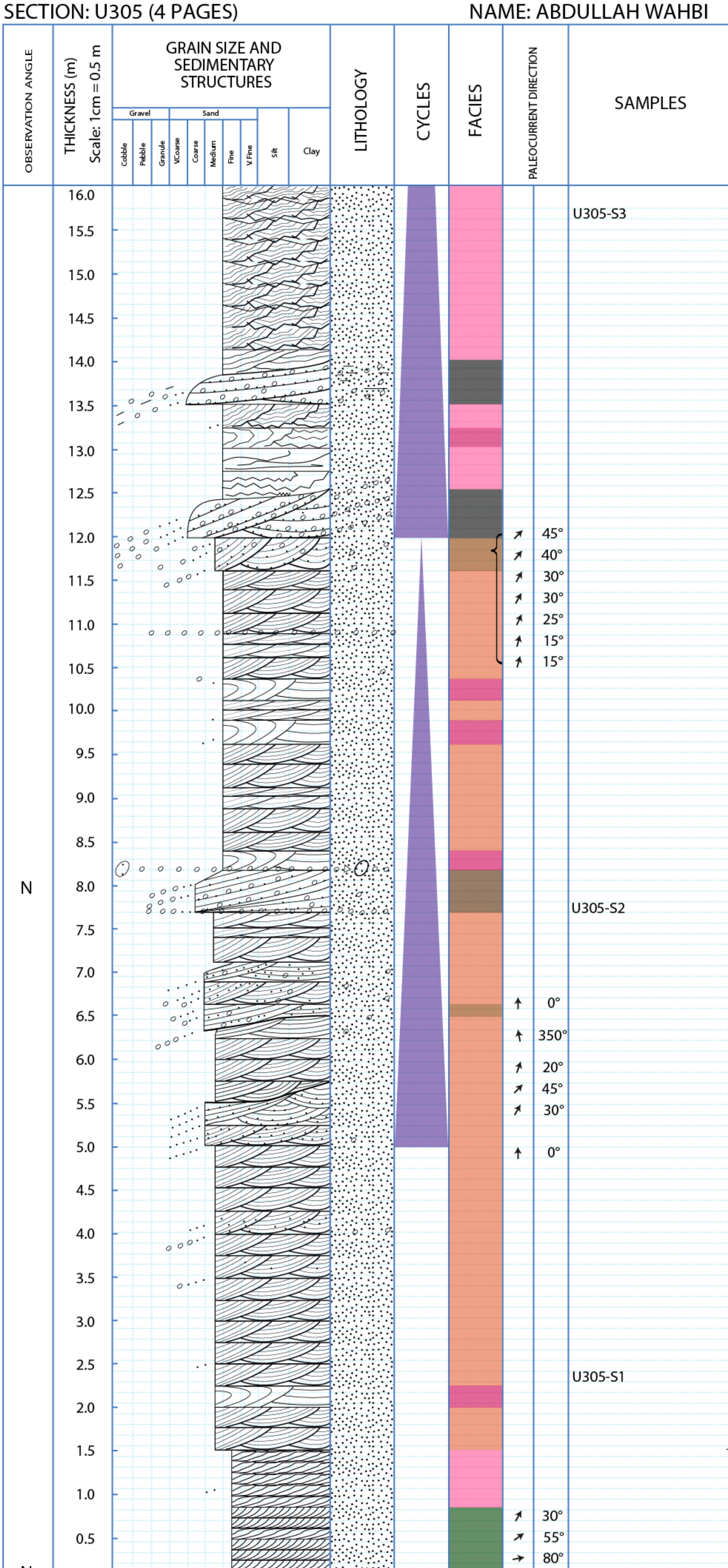


DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l and u)-grained; moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (15-50 cm thick); fining-upward trend; sand- to pebble-size angular to well-rounded quartz are observed concentrated at bases of sets and foresets; CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS bed is observed within bedding

CITY/TOWN: Al Ula

SECTION: U305 (4 PAGES) NAME: ABDULLAH WAHBI LOCATION: N 26° 44.000’, E 38° 02.300’



DESCRIPTION / REMARKS

SANDY CROSS-BEDDED CONGLOMERATE: white; very coarse (l)-grained; very poorly-sorted; sub-angular; cross-bedded sets (up to 100 cm thick); abundant scouring; bedding shows concentrations of sand- to pebble-size quartz and mud clasts at bases of sets and foresets; bedding show DEFORMED SANDSTONE beds above and below conglomerate beds

(CONGLOMERATIC) (PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white, tan to orange; medium (l)- to coarse (u)-grained; well- to moderately-sorted; sub- to well-rounded; (conglomeratic) (pebbly) trough cross-bedded sets (10-30 cm thick; up to 50 cm thick); fining-upward trend; abundant scouring and truncations; concentrations of sand- to pebble-size quartz at bases of sets and foresets; bedding shows DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds; recurring lags show concentrations of pebble-size well-rounded quartz and rare granitic fragments and sandstone clasts

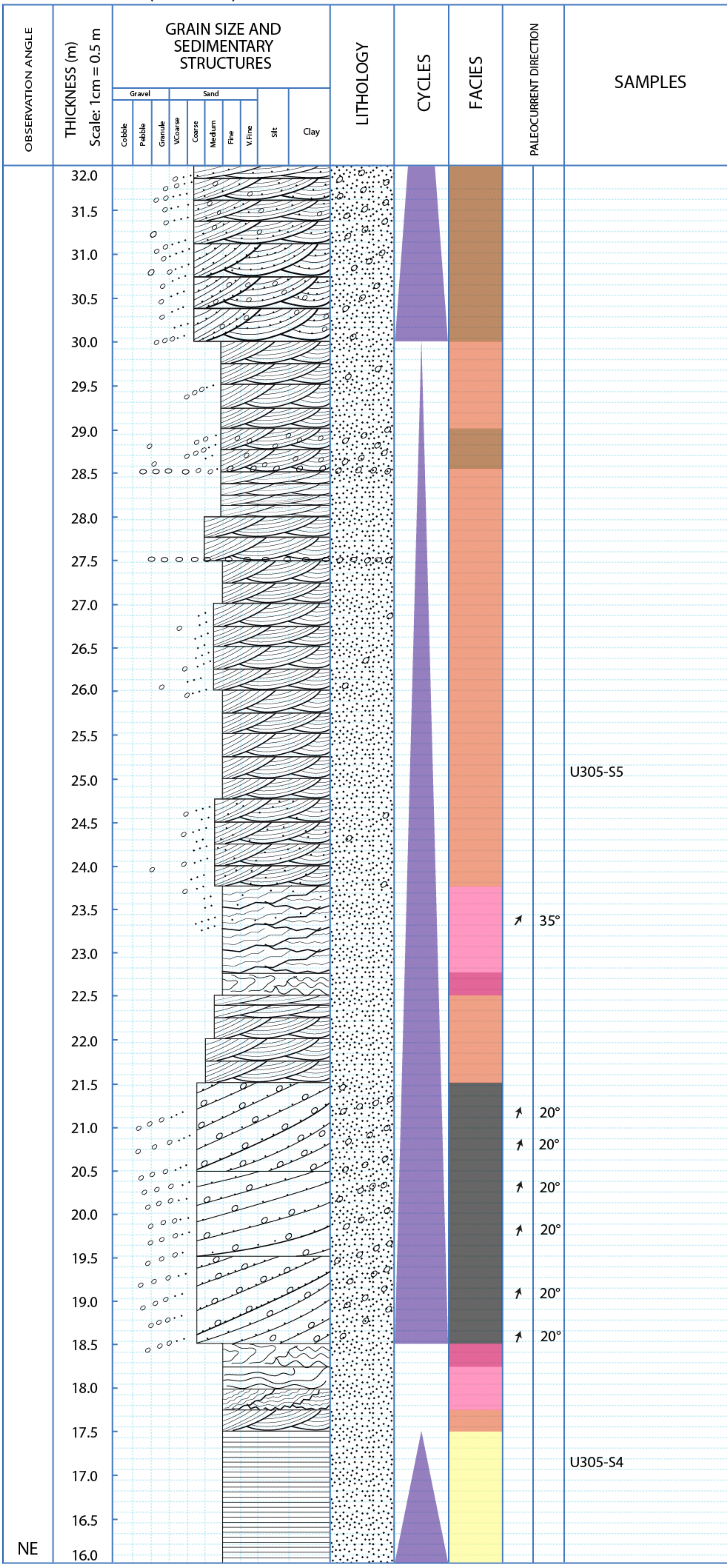
THINLY-BEDDED TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); fine (u)-grained; well- to moderately-sorted; sub- to well-rounded; thinly-bedded tangential to sigmoidal cross-bedded sets (<10 cm thick); bedding overlain by DEFORMED SANDSTONE beds show evidence of failure of deposited tangential to sigmoidal cross-bedded sets

CITY/TOWN: Al Ula

SECTION: U305 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 44.000', E 38° 02.300'



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); medium (l)- to coarse (u)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (<10-30 cm thick); fining-upward trend; concentrations of sand- to pebble-size, well-rounded quartz at bases of sets and foresets; bedding contains DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds; recurring lags show concentrations of pebble-size quartz (up to 5 cm in size)

SANDY CROSS-BEDDED CONGLOMERATE: white; coarse (u)-grained; very poorly-sorted; sub-angular; cross-bedded sets (up to 100 cm thick); bedding shows concentrations of sand- to pebble-size quartz at bases of foresets

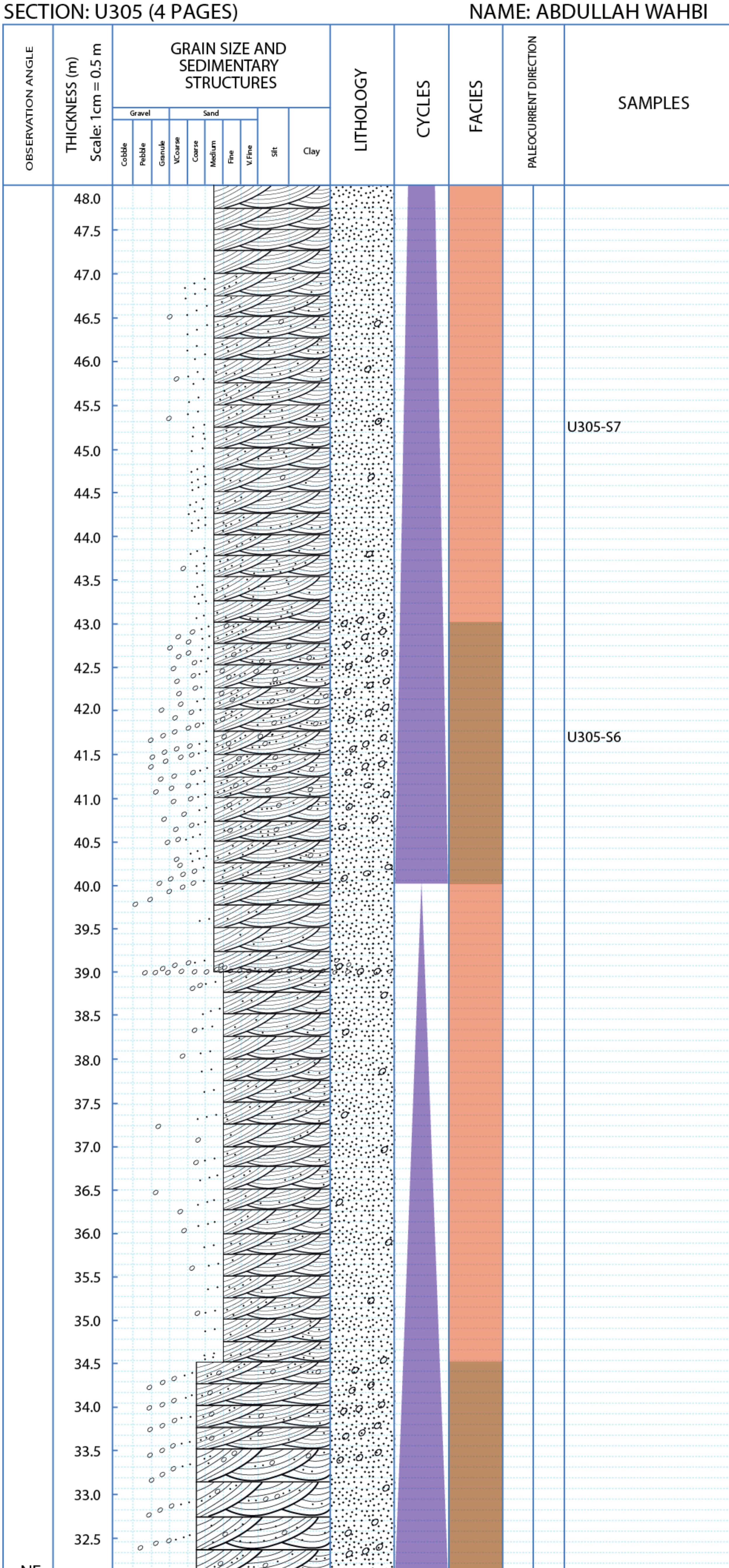
FLAT-LAMINATED SANDSTONE: white; medium (l)-grained; well- to moderately-sorted; sub- to well-rounded; flat-laminated sandstone beds; topped by a TROUGH CROSS-BEDDED SANDSTONE, DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

CITY/TOWN: Al Ula

SECTION: U305 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 44.000′, E 38° 02.300′



DESCRIPTION / REMARKS

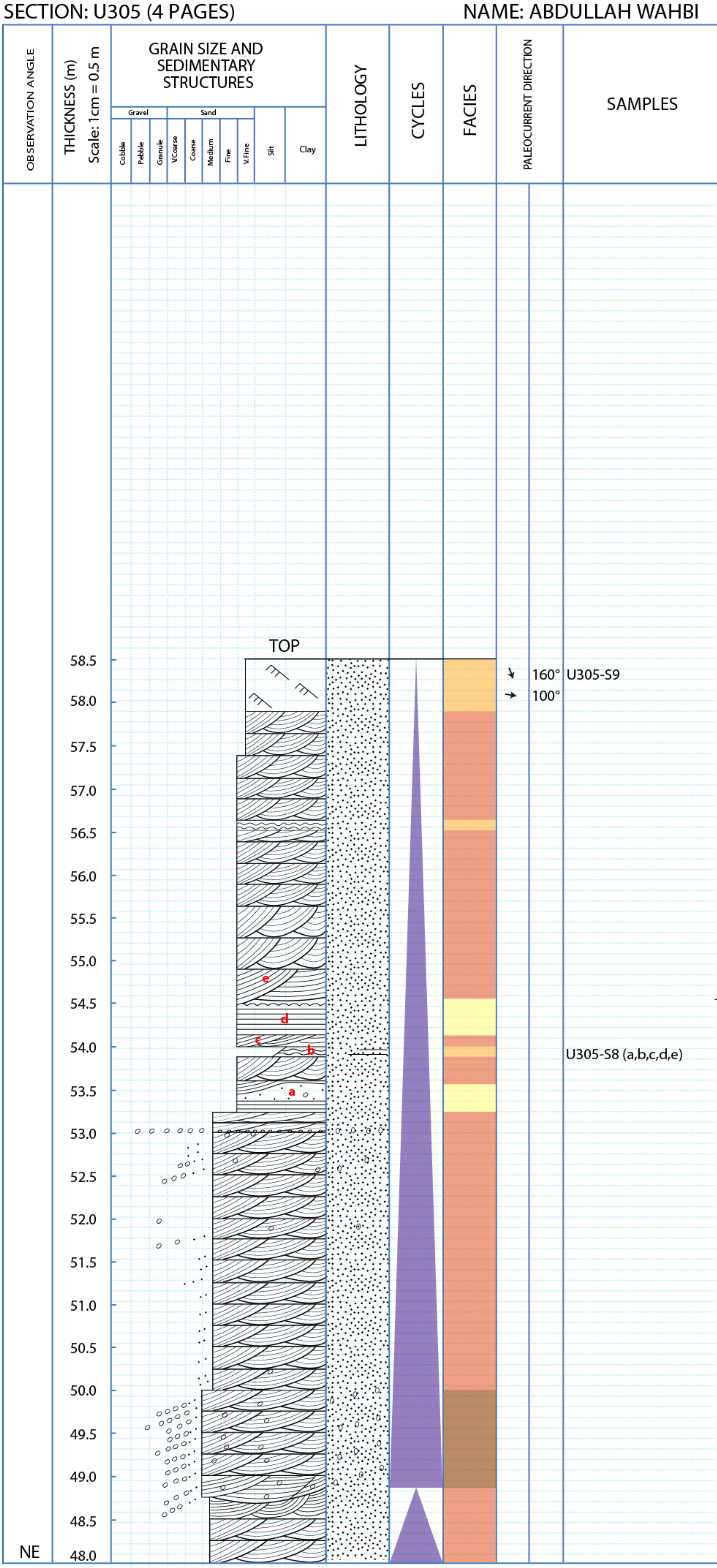
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white, buff to orange (weathering); medium (l)- to coarse (u)-grained; moderately- to poorly-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (consistently found at ~ 20 cm thickness); bedding shows concentrations of sand- to pebble-size angular to well-rounded quartz (variable in sizes between 1-10< cm in size) at bases of beds, sets and foresets; lags show concentrations of pebble-size quartz (angular to well-rounded)

CITY/TOWN: Al Ula

SECTION: U305 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 44.000′, E 38° 02.300′



DESCRIPTION / REMARKS

TROUGH CROSS-BEDDED SANDSTONE: orange to tan; very fine (u)- to fine (l)-grained; well-sorted; sub- to well-rounded; trough cross-bedded sets (10-25 cm thick); fining-upward trend into LENTICULAR- TO WAVY- AND RIPPLE-LAMINATED SANDSTONE beds

LENTICULAR-, WAVY- AND FLAT-LAMINATED TO MASSIVE SANDSTONE: white to maroon-purple; fine (l)-grained; argillaceous; well- to moderately-sorted; well-rounded; alternating discontinuous-lenticular- and wavy- to flat-laminated and massive sandstone beds, interbedded with TROUGH CROSS-BEDDED SANDSTONE; variable cementation

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white, buff to orange (weathering); medium (u)- to coarse (l)-grained; well- to moderately-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (10-20 cm thick); local concentrations of sand- to pebble-size quartz at bases of sets and foresets; lag shows concentrations of pebble-size quartz

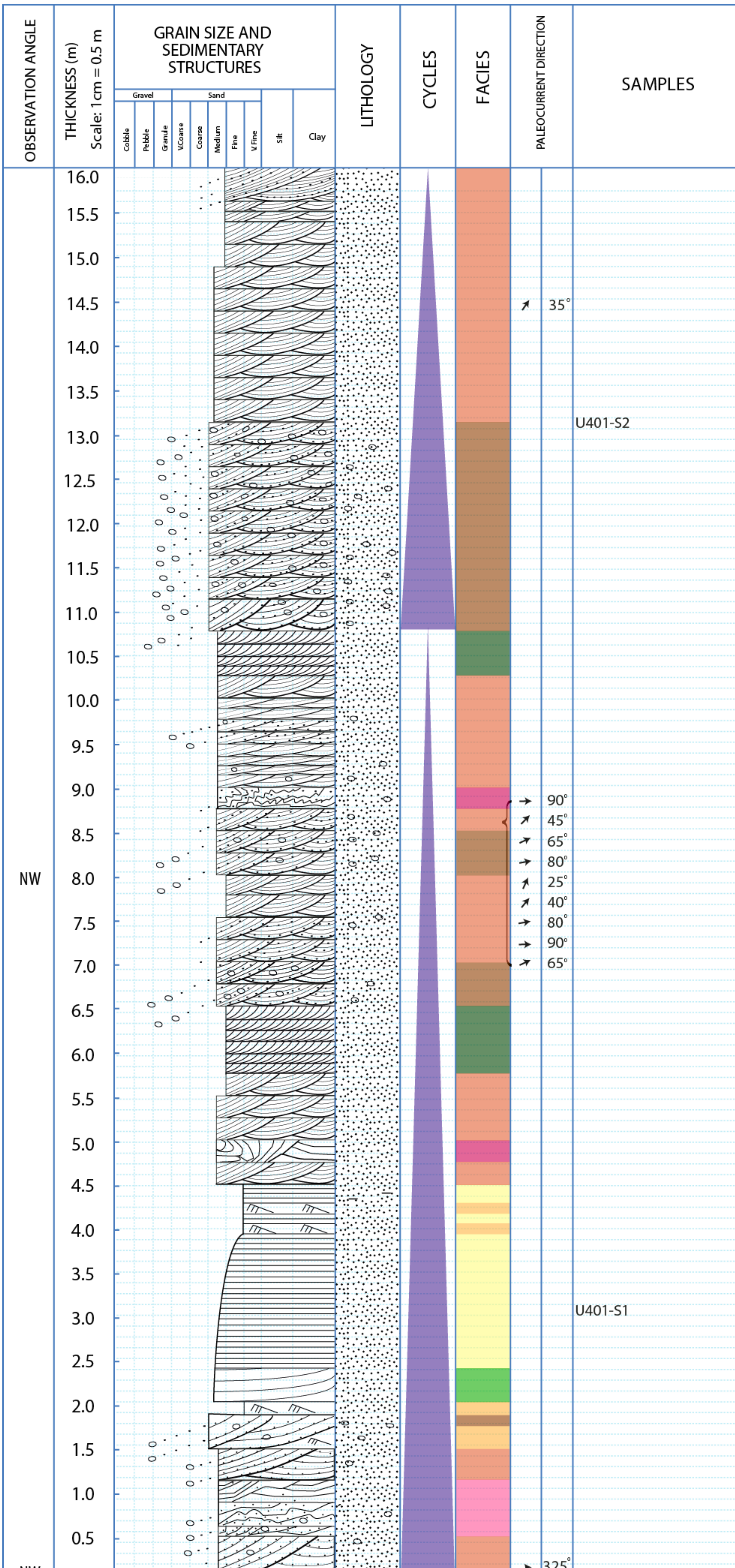
CITY/TOWN: Al Ula

PAGE 1 OF 4

SECTION: U401 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.579′, E 37° 54.589′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (l)- to coarse (l)-grained; sets range from poorly- to well-sorted, sub- to well-rounded; (pebbly) trough cross-bedded beds (<10-30 cm thick); fining-upward cycles into finer-grained and thinner sets; inclusions within coarser-grained sets show pebble-size quartz and rare feldspars concentrated at bases of sets and randomly distributed within bedding; some sets develop (THINLY-BEDDED) TANGENTIAL CROSS-BEDDED SANDSTONE sets; bedding shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

RIPPLE- AND FLAT-LAMINATED SANDSTONE: tan, orange to purple; fine (l)- to medium (u)-grained; well- to moderately-sorted; sub- to well-rounded; basal bed shows LOW-ANGLE TANGENTIAL CROSS-BEDDED SANDSTONE; fining-upward into ripple- and flat-laminated sandstone beds; top is silty to argillaceous

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange; medium (u)- to coarse (l)-grained; moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (<10-40 cm thick); bedding includes pebble-size quartz (up to 2 cm) and some feldspars; recurring truncations and scouring; fining-upward into maroon, fine (l)-grained, micaceous LENTICULAR- TO RIPPLE-LAMINATED SANDSTONE beds; some beds display DEFORMED SANDSTONE bedding

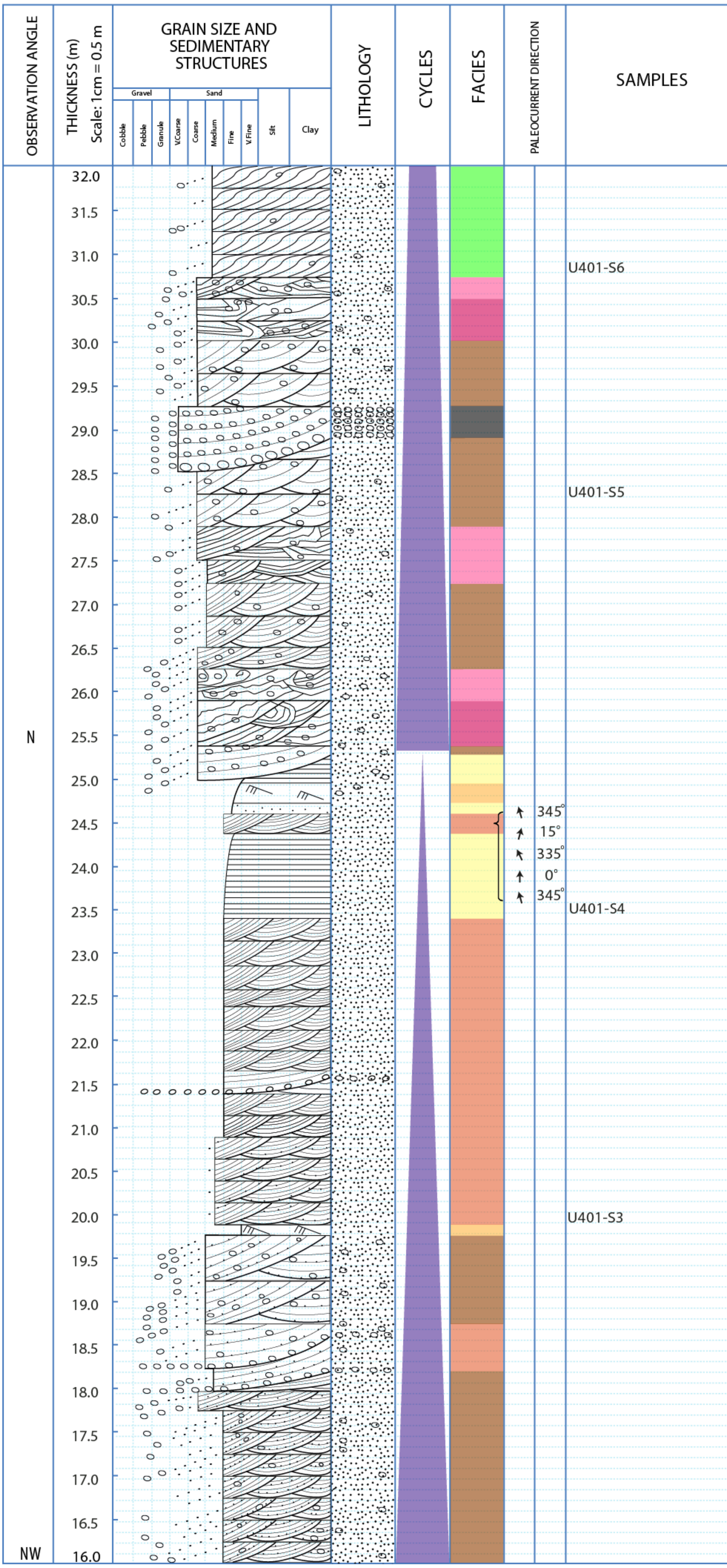
CITY/TOWN: Al Ula

PAGE 2 OF 4

SECTION: U401 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.579′, E 37° 54.589′



DESCRIPTION / REMARKS

CROSS-BEDDED SANDSTONE: white; orange and tan (weathering); medium (u)- to coarse (u)-grained; moderately- to poorly-sorted; sub- to well-rounded; bedding dominated by PEBBLY TROUGH CROSS-BEDDED sets (10-50 cm thick); abundance of truncations; show concentrations of sand- to pebble-size well-rounded (2-7 cm in size), often concentrated at bases of sets and foresets; DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within bedding; one bed shows SANDY CROSS-BEDDED CONGLOMERATE (at 28.5 m; ~150 cm thick); bedding develops into SIGMOIDAL CROSS-BEDDED SANDSTONE sets (~ 20 cm thick); fining-upward cycles

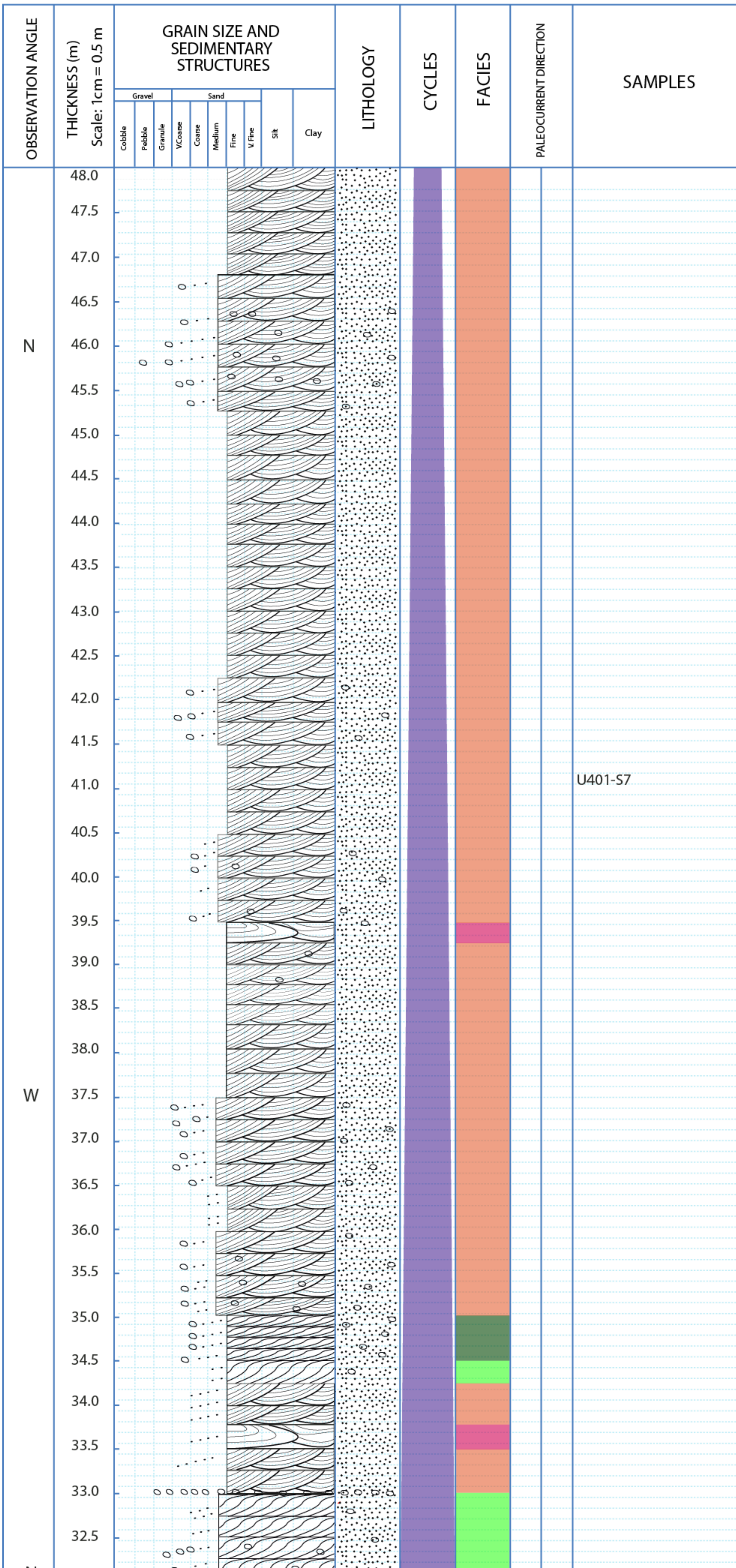
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: tan to orange, medium (l)- to coarse (u)-grained; well- to poorly-sorted; sub- to well-rounded; (pebbly) trough cross-bedded sets (10-40 cm thick); coarser beds show concentration of sand- to pebble-size quartz; fining-upward into medium (l)-grained LENTICULAR- TO RIPPLE-LAMINATED and FLAT-LAMINATED TO MASSIVE SANDSTONE beds; lags show pebble-size quartz (up to 4 cm in size)

CITY/TOWN: Al Ula

SECTION: U401 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.579′, E 37° 54.589′



DESCRIPTION / REMARKS

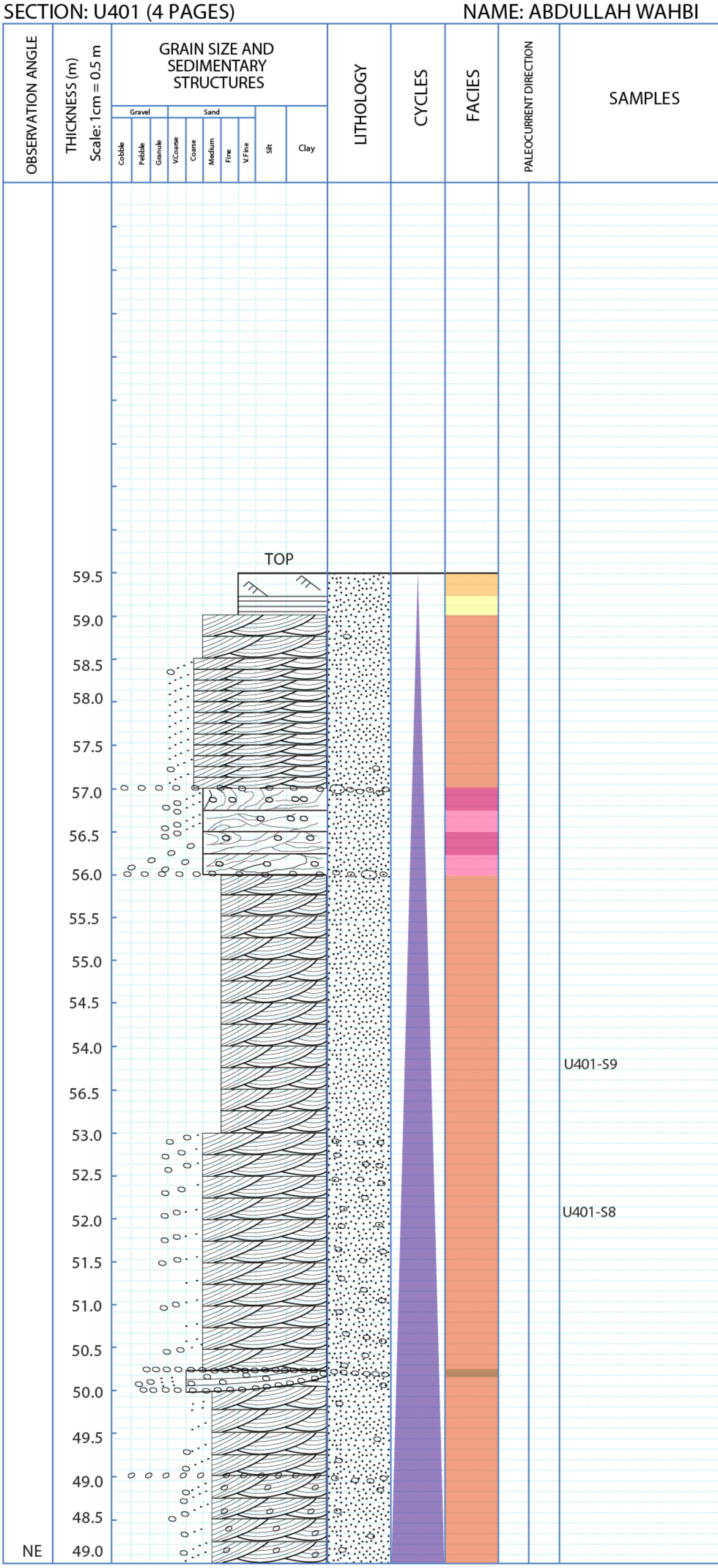
TROUGH CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); medium (l and u)-grained; well- to poorly-sorted; sub- to well-rounded; trough cross-bedded sets (10-30 cm thick); abundant truncations; coarser-grained sets show inclusions of sand- to pebble-size quartz (2-5 cm in size; up to 8 cm in size in lowermost bed); minor presence of CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds; minor development into (THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED SANDSTONE sets; lags show pebble-size quartz (up to 4 cm in size)

CITY/TOWN: Al Ula

SECTION: U401 (4 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 26° 47.579′, E 37° 54.589′



DESCRIPTION / REMARKS

TROUGH CROSS-BEDDED SANDSTONE: white; orange to tan (weathering); medium (l)- to coarse (u)-grained; well- to poorly-sorted; sub- to well- rounded; trough cross-bedded sets (<10-30 cm thick; pebbly in one set); truncations are abundant; coarser-grained sets include minor sand- to pebbles-size quartz (2-8 cm); fining-upward trend into tan to maroon, fine (l)-grained RIPPLE-LAMINATED and FLAT-LAMINATED SANDSTONE beds; lags show concentrations of sand- to pebble-size quarts, some feldspars and rare sandstone clasts

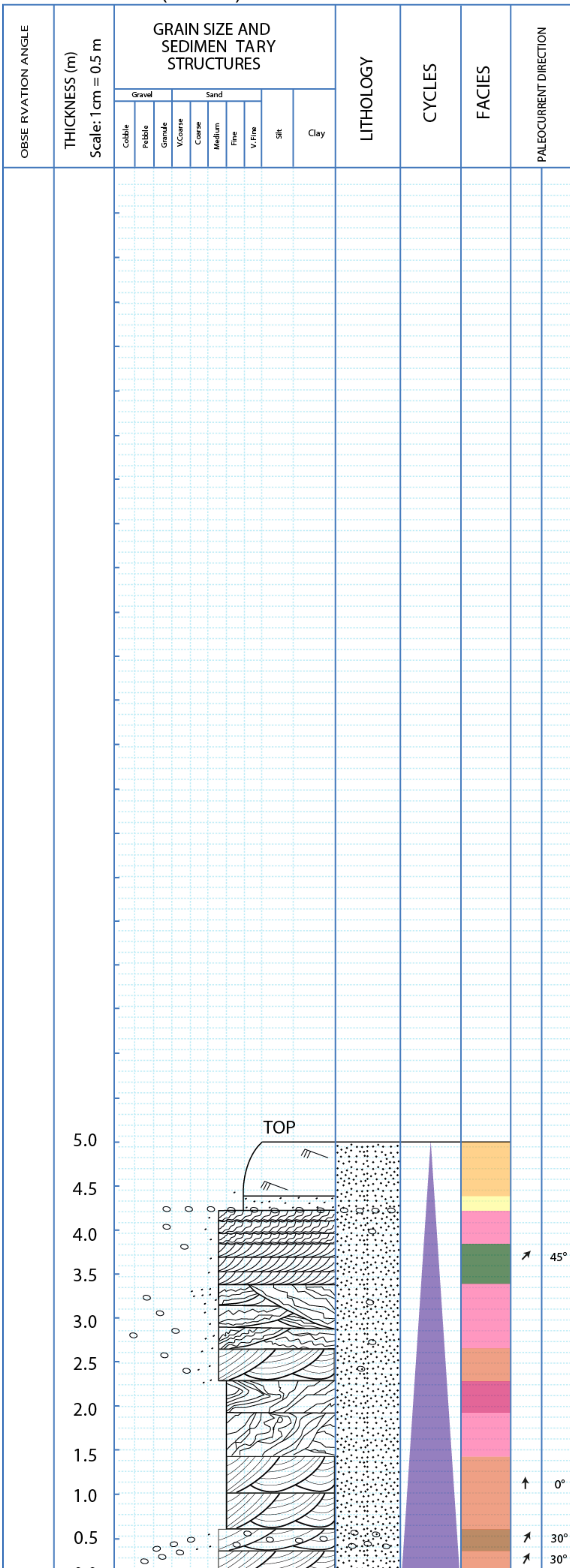
CITY/TOWN: Al Ula

PAGE 1 OF 1

SECTION: U501a (1 PAGE)

NAME: ABDULLAH WAHBI

LOCATION: N 27° 02.126′, E 37° 49.000′



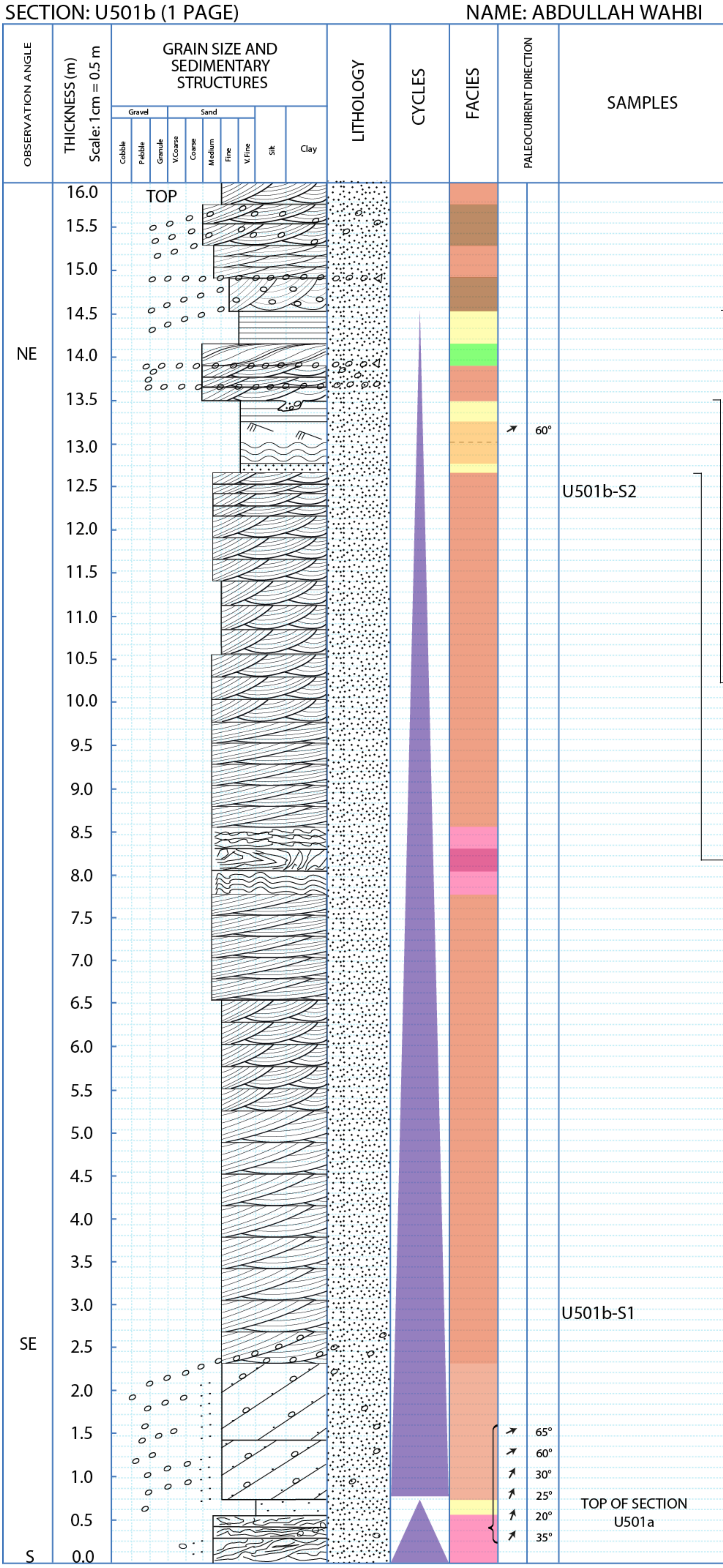
SAMPLES	DESCRIPTION / REMARKS
	LENTICULAR TO RIPPLE-LAMINATED AND MASSIVE SANDSTONE: white, grey, purple to maroon; very fine (l)- to fine (l)-grained; silty; micaceous in places; well-sorted; sub- to well-rounded; discontinuous lenticular- to ripple-laminated and massive sandstone beds
U501a-S3 U501a-S2 U501a-S1	(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white; medium (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; trough cross-bedded sets (<10-40 cm thick); local concentrations of sand- to pebble- size quartz (up to 4 cm in size); sets develops THINLY-BEDDED TANGENTIAL CROSS-BEDDED SANDSTONE sets; both DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within bedding

CITY/TOWN: Al Ula

SECTION: U501b (1 PAGE)

NAME: ABDULLAH WAHBI

LOCATION: N 27° 01.858′, E 37° 48.828′



DESCRIPTION / REMARKS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white to tan (weathering); medium (l)- to coarse (l)-grained; well- to moderately-sorted; sub-rounded to rounded; (pebbly) trough cross-bedded sets (<10-25 cm thick; abundant truncations; coarse-grained sets show concentrations of angular to well-rounded, poorly-sorted sand- to pebble-size quartz (up to 5 cm in size) along bases of sets and foresets; lag shows pebble-size quartz and granitic fragments

CROSS-BEDDED SANDSTONE: white to tan (weathering); coarse (l)-grained; well- to moderately-sorted; sub-rounded to rounded; thinly-bedded TROUGH CROSS-BEDDED sets (<10 cm thick) and one SIGMOIDAL CROSS-BEDDED set (~15 cm thick) showing bundled foresets; sets show minor concentrations of sand- to pebble-size well-rounded quartz; bedding topped by fine (l)-grained, silty FLAT-LAMINATED SANDSTONE bed (truncated in places by overlain bedding); recurring discontinuous and continuous lags, showing concentrations of sand- to pebble-size quartz and granitic fragments

WAVY-, RIPPLE- TO FLAT-LAMINATED AND MASSIVE SANDSTONE: tan, grey, greenish-grey, purple to maroon (weathering); fine (l)-grained; silty in places; well- to moderately-sorted; sub-rounded to rounded; wavy- to ripple-laminated, flat-laminated and silty-massive sandstone beds; top of bedding scoured by overlying trough cross-bedded set

TROUGH CROSS-BEDDED SANDSTONE: white to tan (weathering); medium (l and u)-grained; well- to moderately-sorted; sub-rounded to rounded; trough cross-bedded sets (10-30 cm thick); fining-upward trend; DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within bedding

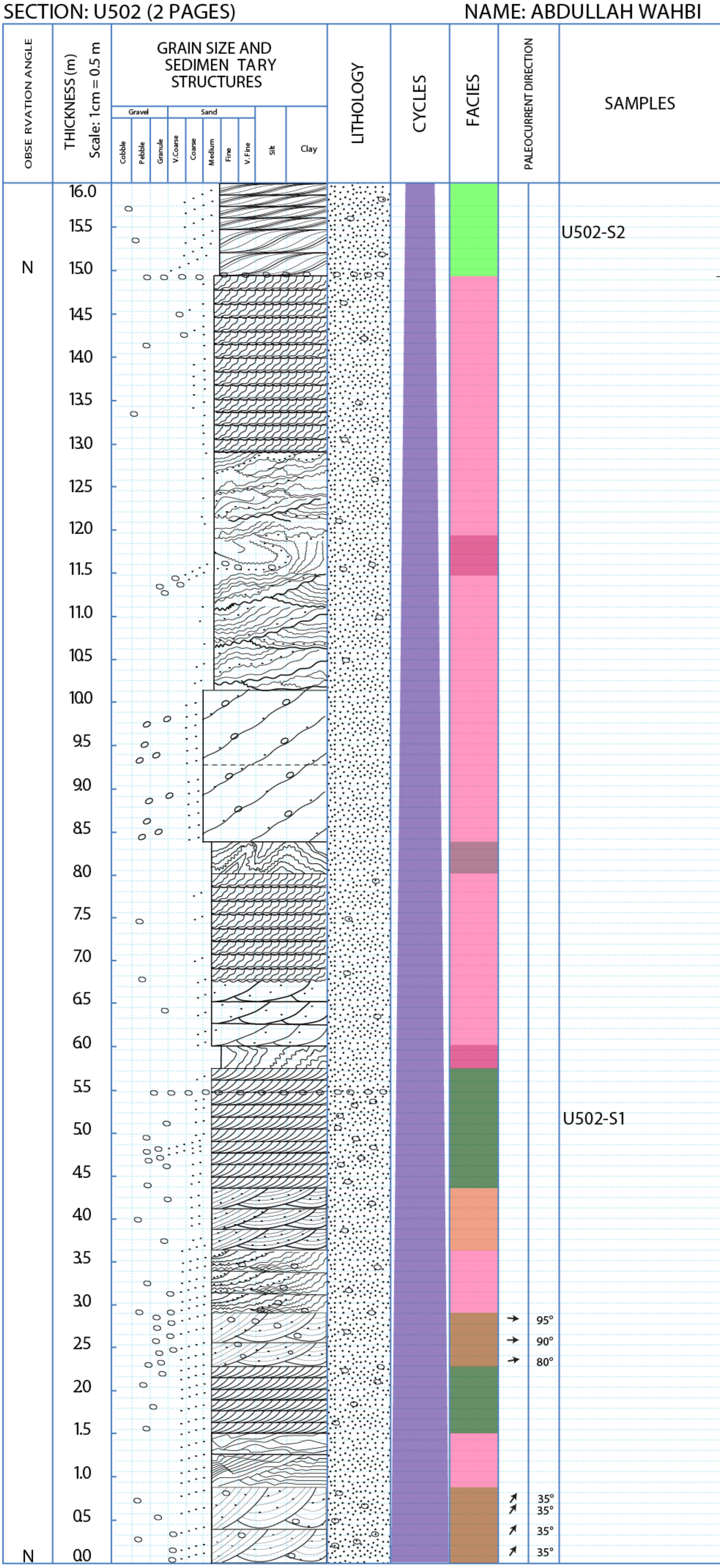
(PEBBLY) PLANAR TABULAR CROSS-BEDDED SANDSTONE: white and tan (weathering); medium (l)-grained; well- to moderately-sorted; sub-rounded to rounded; planar tabular cross-bedded sets (up to 75 cm thick); minor concentrations of sand- to pebble-size quartz at bases of foresets; bedding observed overlying DEFORMED SANDSTONE (medium (u)-grained; 10-20 cm thick) and MASSIVE SANDSTONE beds (equivalent to top of section U501a)

CITY/TOWN: Al Ula

SECTION: U502 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 27° 07.440’, E 37° 50.693’



DESCRIPTION / REMARKS

SIGMOIDAL CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); medium (l)-grained; well- to moderately-sorted; sub-rounded to rounded; sigmoidal cross-bedded sets (<10-20 cm thick); sets show bundled-foresets; bases of foresets show concentrations of sand-size, angular to rounded quartz (rare quartz pebbles)

DEFORMED (CROSS-BEDDED) SANDSTONE: white, tan to orange (weathering); medium (l)- to coarse (l)-grained; well- to moderately-sorted; sub-rounded to rounded; bedding shows DEFORMED SANDSTONE, CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS and INTENSELY–DEFORMED SANDSTONE BEDS; beds show variable thicknesses (<10-30 cm thick; up to 150 cm thick); original sedimentary structures vary between TROUGH CROSS-BEDDED, PLANAR TABULAR CROSS-BEDDED and THINLY-BEDDED TANGENTIAL CROSS-BEDDED sets; fining-upward trend; local concentrations of sand- to pebble-size quartz

CROSS-BEDDED SANDSTONE: white, tan to orange (weathering); medium (u)-grained; well- to moderately-sorted; sub-rounded to rounded; sets include (PEBBLY) TROUGH CROSS-BEDDED sets (20-30 cm thick), and THINLY-BEDDED TANGENTIAL CROSS-BEDDED sets (<10 cm thick); some sets show concentrations of sand- to pebble-size quartz at bases of sets and foresets; lag surface shows concentrations of pebble-size quartz; DEFORMED SANDSTONE beds are observed within bedding

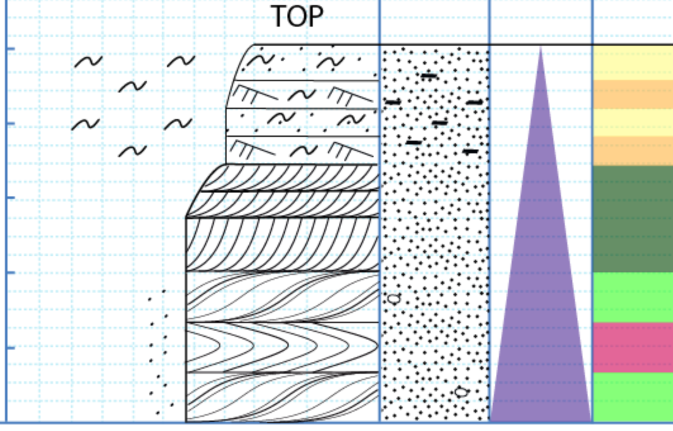
CITY/TOWN: Al Ula

SECTION: U502 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 27° 07.440′, E 37° 50.693′

OBSE RVATION ANGLE	THICKNESS (m) Scale: 1 cm = 0.5 m	GRAIN SIZE AND SEDIMEN TARY STRUCTURES (Gravel: Cobble, Pebble, Granule; Sand: V.Coarse, Coarse, Medium, Fine, V. Fine; Silt; Clay)	LITHOLOGY	CYCLES	FACIES	PALEOCURRENT DIRECTION	SAMPLES	DESCRIPTION / REMARKS
	18.5	TOP					U502-S3-2	LENTICULAR- TO RIPPLE-LAMINATED AND MASSIVE SANDSTONE: white, light grey, purple and maroon; very fine (l)- to fine (l)-grained; silty and argillaceous; well- to moderately-sorted; sub- to well-rounded; discontinuous lenticular- to ripple-laminated and massive sandstone beds; some beds show trace fossils (*Cruziana*; >20 cm in length in places and up to 8 cm in width; includes other trace fossils)
	18.0						U502-S3-1	
	17.5							(THINLY-BEDDED) TANGENTIAL TO SIGMOIDAL CROSS-BEDDED SANDSTONE: white to tan (weathering); fine (l)- to medium (u)-grained; moderately-sorted; sub-angular to sub-rounded; sigmoidal cross-bedded sets (20-30 cm thick) showing bundled foresets with coarser-grained foresets bases; bedding develops into finer-grained, thinly-bedded tangential cross-bedded sets (<10 cm thick); fining-upward trend; one bed shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS
N-W	17.0							
	16.5							
NW	16.0							



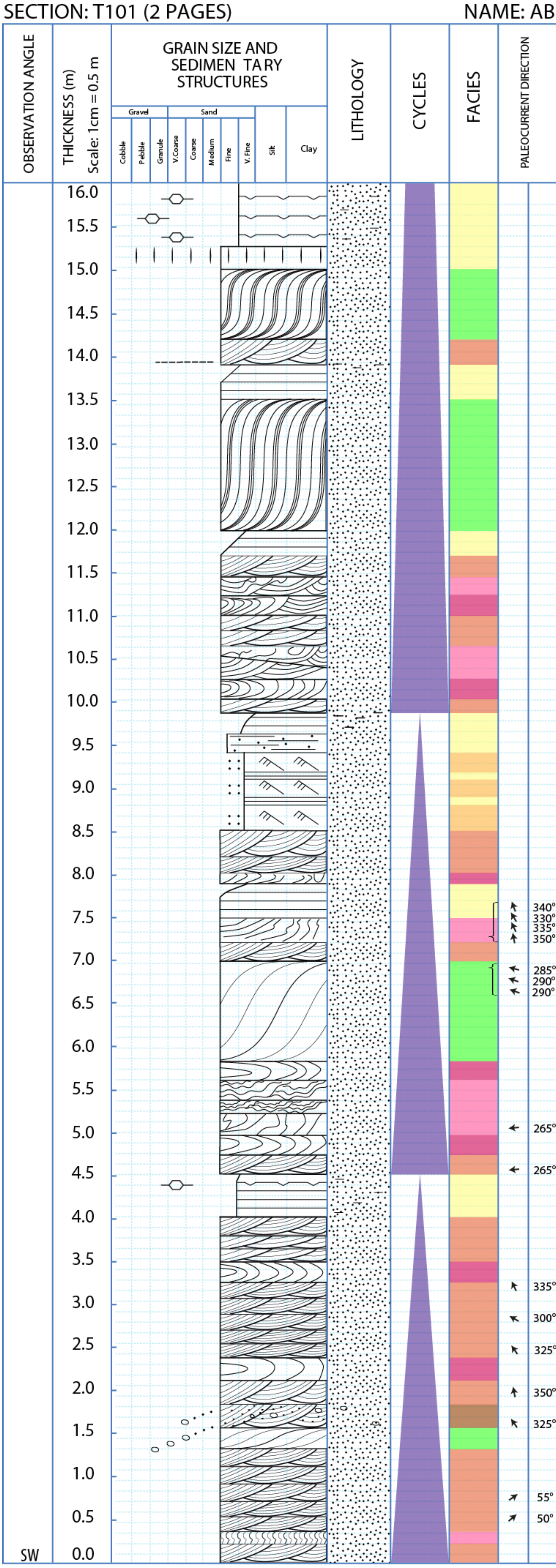
3.2 TABUK STUDY AREA

CITY/TOWN: Tabuk - Ash' Shiq

SECTION: T101 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 03.287', E 35° 55.629'



SAMPLES
T101-S7
T101-S6
T101-S5
T101-S4
T101-S3
T101-S2
T101-S1

DESCRIPTION / REMARKS

MASSIVE SANDSTONE: white to dark purple (weathering); fine (l)- to medium (l)-grained; silty to argillaceous; moderately-sorted; sub-angular to sub-rounded; massive sandstone beds; bedding shows evidence of burrowing (at ~15.0 cm; *skolithos*; 3-7 cm long); multiple beds show mud cracks (syneresis mud cracks; between 15.5 and 16.0 cm)

CROSS-BEDDED SANDSTONE: orange, maroon and greenish-grey (weathering); fine (l)- to medium (l)-grained; moderately-sorted; sub-angular to sub-rounded; bedding includes thin TROUGH CROSS-BEDDED sets (10-20 cm thick) and thick SIGMOIDAL CROSS-BEDDED sets (up to 150 cm thick); sigmoidal cross sets show bundled-foresets; fining-upward trend into silty to argillaceous FLAT-LAMINATED SANDSTONE beds; bedding shows DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

LENTICULAR- TO RIPPLE- AND FLAT-LAMINATED SANDSTONE: dark maroon; very fine (u)- to fine (u)-grained; locally silty; moderately- to poorly-sorted; sub-angular to sub-rounded; interbedded lenticular-ripple-laminated and flat-laminated to massive sandstone beds

TROUGH CROSS-BEDDED SANDSTONE: orange-brown; medium (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-40 cm thick); one set develops SIGMOIDAL CROSS-BEDDED SANDSTONE set (up to 100 cm in thickness); fining-upward into FLAT-LAMINATED SANDSTONE beds; DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds are observed within bedding

FLAT-LAMINATED SANDSTONE: white, brown and greenish grey; fine (l)-grained; poorly-sorted; sub-rounded; flat-laminated sandstone beds; maroon concretions observed; bedding topped by mud cracks

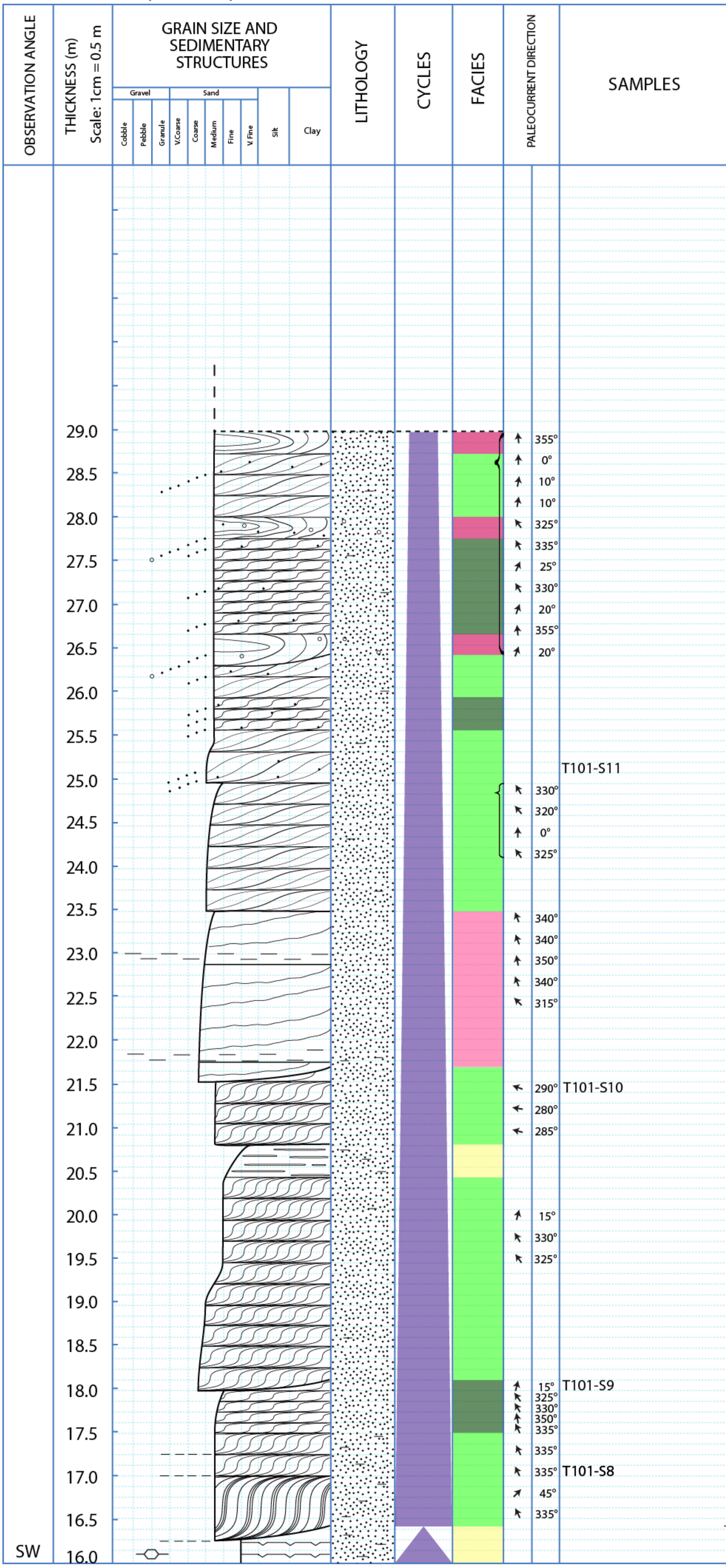
TROUGH CROSS-BEDDED SANDSTONE: reddish-brown; medium (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (10-20 cm thick); includes rare quartz pebbles (up to 1 cm in size); one set develops SIGMOIDAL CROSS-BEDDED SANDSTONE set; some beds show CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS

CITY/TOWN: Tabuk - Ash' Shiq

SECTION: T101 (2 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 03.287', E 35° 55.629'



DESCRIPTION / REMARKS

(THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED SANDSTONE: white to purple (variegated; weathering); medium (l)- to coarse (l)-grained; silty to argillaceous; well- to moderately-sorted; sub- to well-rounded; (thinly-bedded) sigmoidal cross-bedded sets (<10-30 cm thick); fining-upward trend; some sets show concentrations of sand- to pebble-size quartz (up to 2 cm) at bases of sets and foresets; recurring scouring and truncations; bedding shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

DEFORMED (CROSS-BEDDED) SANDSTONE: white to purple (variegated; weathering); medium (u)- to coarse (u)-grained; argillaceous bed bases; well- to moderately-sorted; sub- to well-rounded; deformed sandstone beds (including multiple sets, up to 150 cm thick; cross-bedded to massive); fining-upward trend

(THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED SANDSTONE: white to purple (variegated; weathering); fine (l)- to medium (u)-grained; silty to argillaceous; well- to moderately-sorted; sub- to well-rounded; (thinly-bedded) sigmoidal cross-bedded sets (<10-30 cm thick); some sets show clear bundled-foresets; fining-upward trend into very fine (u)-grained, silty to argillaceous FLAT-LAMINATED SANDSTONE bed; recurring scouring and truncations with argillaceous beds bases

MASSIVE SANDSTONE: white to dark purple (weathering); fine (l)-grained; silty to argillaceous; moderately-sorted; sub-angular to sub-rounded; massive sandstone beds; show of syneresis mud cracks

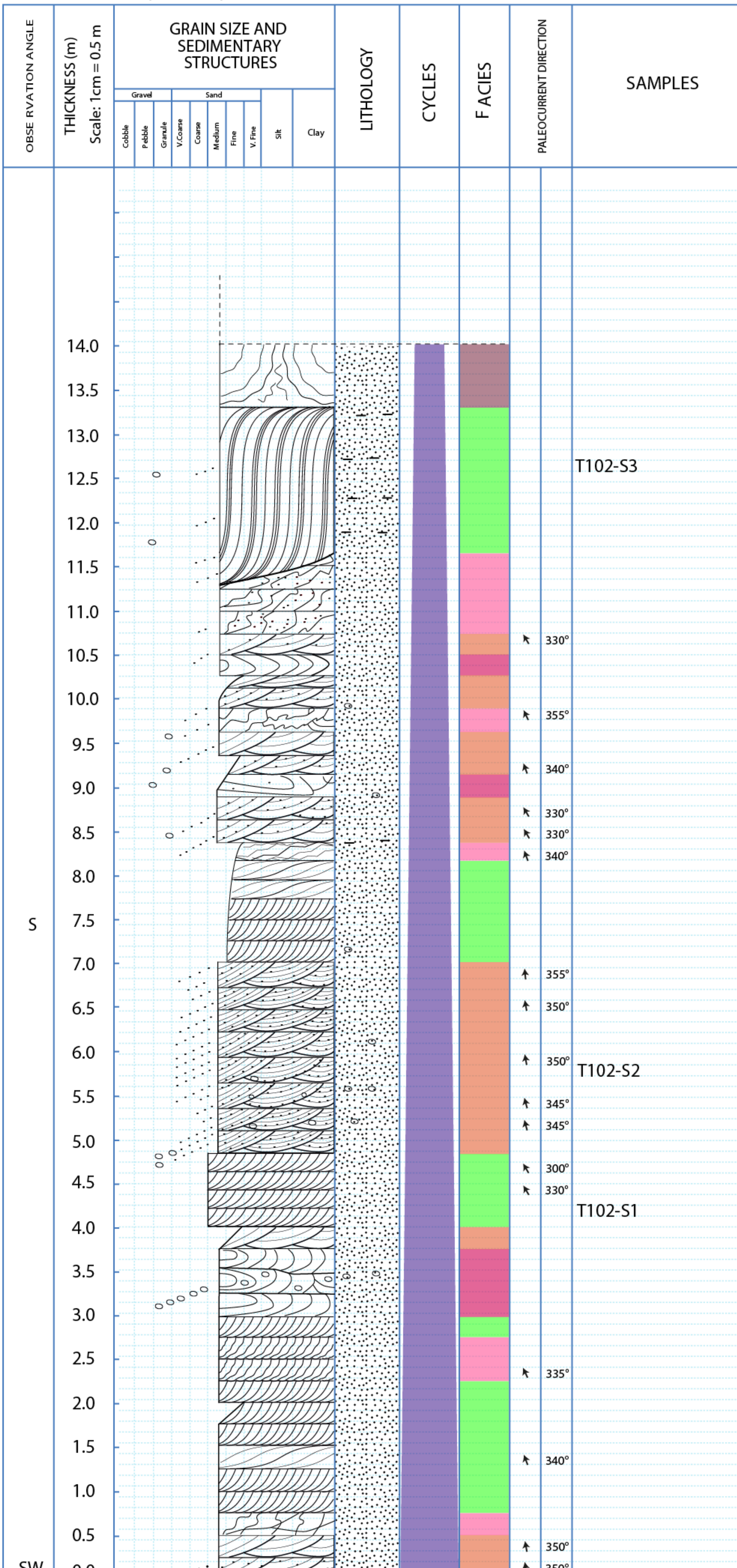
CITY/TOWN: Tabuk - Ash’ Shigri

PAGE 1 OF 1

SECTION: T102 (1 PAGE)

NAME: ABDULLAH WAHBI

LOCATION: N 27° 59.901’, E 35° 59.200’



DESCRIPTION / REMARKS

SIGMOIDAL CROSS-BEDDED SANDSTONE: tan to reddish-brown (weathering); medium (u)-grained; silty to argillaceous; well- to moderately-sorted; sub-angular to sub-rounded; one sigmoidal cross-bedded set (up to 175 cm thick) which show clear bundled-foresets (cm- to dm-scale); scouring observed in underlying surface; random distribution of pebble-size quartz (up to 2 cm in size); overlying INTENSELY-DEFORMED SANDSTONE bed shows fluid-escape structure

CROSS-BEDDED SANDSTONE: tan, maroon and brown-orange (weathering); fine (l)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; cross-bedded sandstone sets include TROUGH CROSS-BEDDED sets (20-30 cm thick; up to 4 m wide) and TANGENTIAL TO SIGMOIDAL CROSS-BEDDED sets (10-15 cm thick); fining-upward trend; minor concentrations of sand- to pebble-size quartz (up to 1 cm) at bases of sets and foresets; bedding shows DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

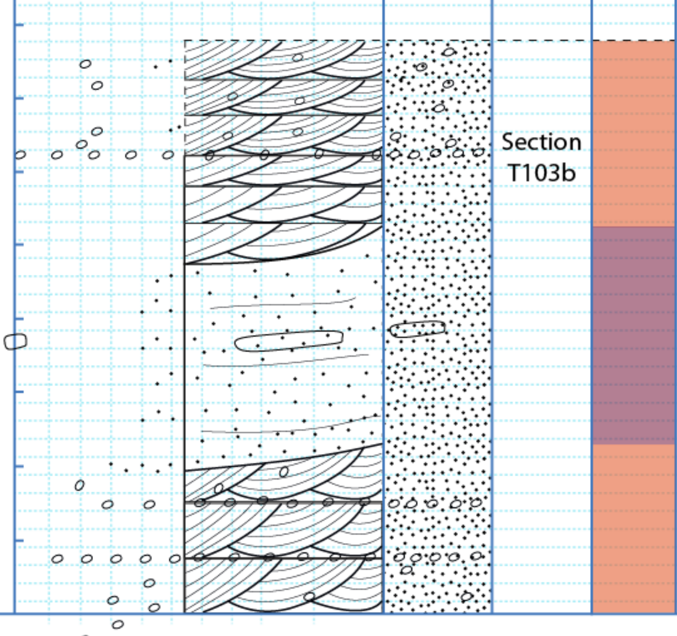
CITY/TOWN: Tabuk - Bajdah

SECTION: T103a (1 PAGE)

NAME: ABDULLAH WAHBI

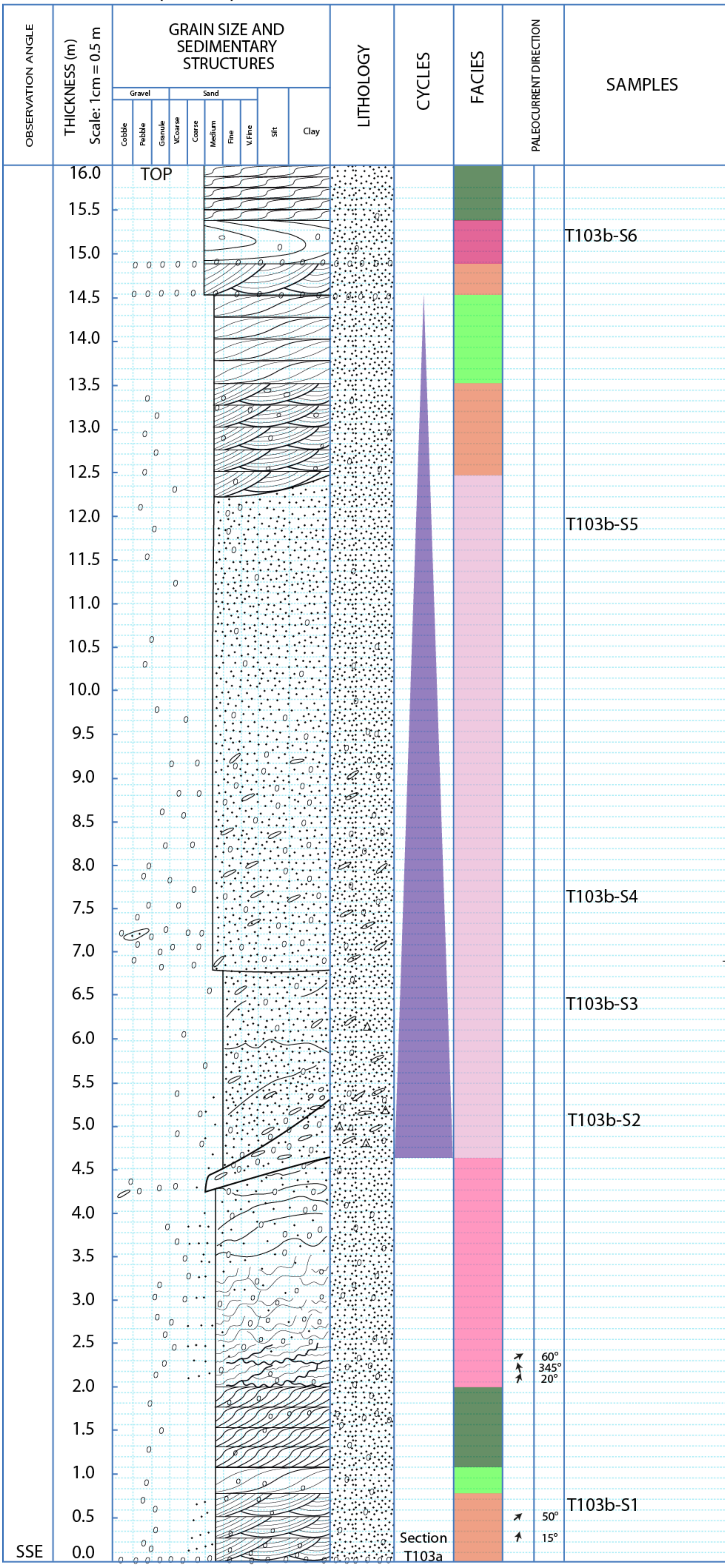
LOCATION: N 28° 04.017', E 35° 58.964'

OBSERVATION ANGLE	THICKNESS (m) Scale: 1cm = 0.5 m	GRAIN SIZE AND SEDIMENTARY STRUCTURES (Gravel: Cobble, Pebble, Granule; Sand: V.Coarse, Coarse, Medium, Fine, V.Fine; Silt; Clay)	LITHOLOGY	CYCLES	FACIES	PALEOCURRENT DIRECTION	SAMPLES	DESCRIPTION / REMARKS
	4.0							
	3.5							TROUGH CROSS-BEDDED SANDSTONE: tan to variegated (weathering); medium (u)-grained; poorly-sorted; sub-angular to sub-rounded; trough cross-bedded sets (20-40 cm thick); minor concentrations of sand- to pebble-size quartz at bases of foresets; evidence of scouring; lags show concentrations of pebble-size well-rounded quartz; one INTENSELY-DEFORMED SANDSTONE bed shows random concentrations of coarser-sand grains and sandstone clasts (up to 1 m in size); lag at ~3.0 m is the base of section T103b
	3.0			Section T103b				
	2.5							
	2.0							
	1.5							
	1.0							
	0.5							
NE	0.0							



CITY/TOWN: Tabuk - Bajdah

SECTION: T103b (1 PAGE) NAME: ABDULLAH WAHBI LOCATION: N 28° 04.017′, E 35° 58.964′



DESCRIPTION / REMARKS

CROSS-BEDDED SANDSTONE: white to purple and grey (weathering); medium (u)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to well-rounded; cross-bedded sandstone sets include TROUGH CROSS-BEDDED sets (10-30 cm thick) and (THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED sets (<10-30 cm thick); minor concentrations of sand- to pebble-size quartz (up to 3 cm) at bases of sets and foresets; recurring lags show concentrations of pebble-size quartz (up to 5 cm in size; mostly well-rounded); one bed shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS; variable cementation

VERY POORLY-SORTED PARACONGLOMERATE: dark purple (weathering); medium (u)- grained; sub-angular to sub-rounded; bedding shows very poorly-sorted gravel component, supported in very poorly-sorted sandstone matrix; significant concentrations of sand- to pebble-size quartz and rare granitic fragments (5-15 cm in size; variable shapes) which display grading; variable cementation

VERY POORLY-SORTED PARACONGLOMERATE: dark grey to purple (weathering); medium (l)- to coarse (l)-grained; sub-angular to sub-rounded; bedding shows very poorly-sorted gravel component, supported in very poorly-sorted sandstone matrix; significant concentrations of sand- to pebble-size quartz (2-10 cm in size; well-rounded, sub-rounded, elongated, and fragmented – broken) and granitic fragments (2-5 cm in size; well-rounded and fragmented – broken); variable cementation

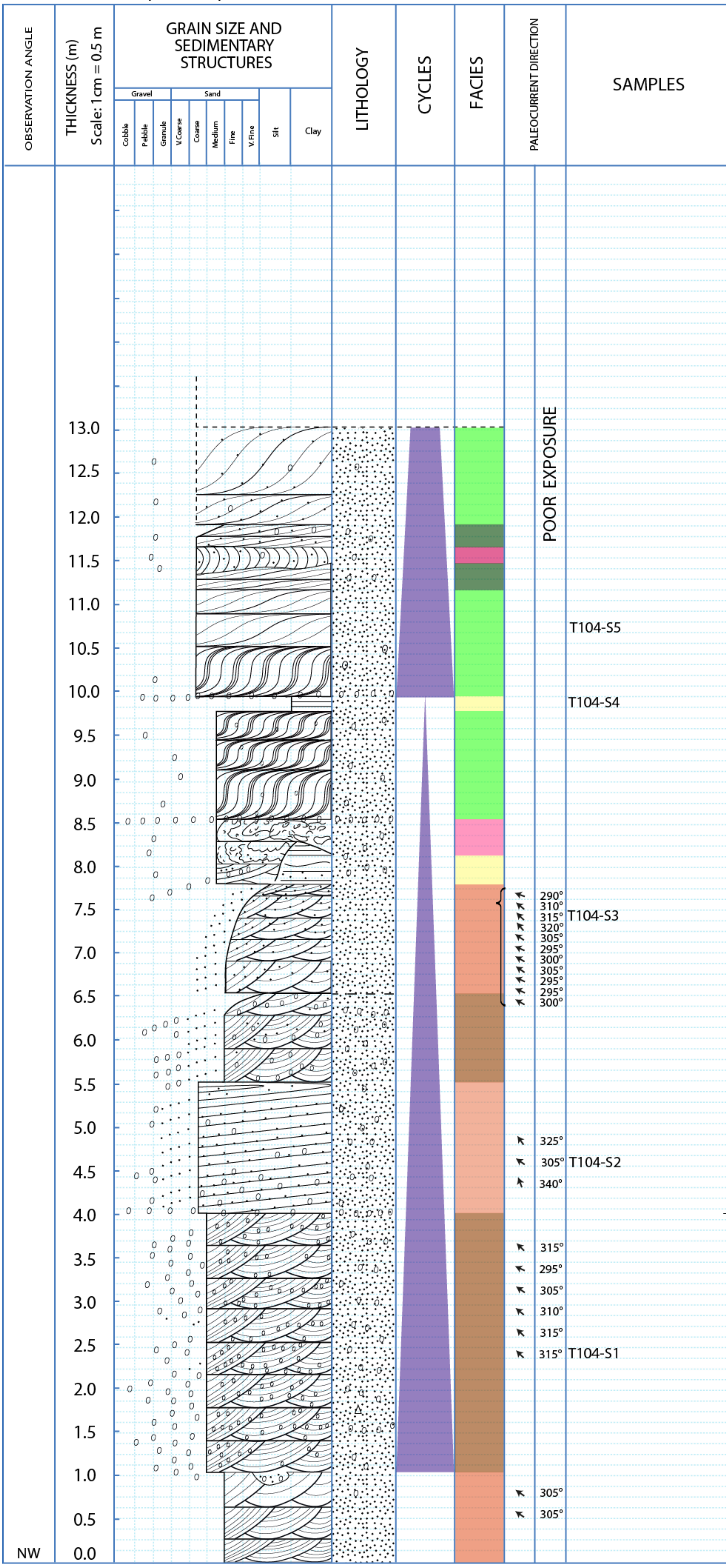
CROSS-BEDDED SANDSTONE: white to purple and dark grey (weathering); medium (u)-grained; poorly-sorted; sub-angular to sub-rounded; cross-bedded sandstone sets include TROUGH CROSS-BEDDED sets (15-30 cm thick) and (THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED sets (<10-30 cm thick); minor concentrations of sand- to pebble-size quartz (up to 5 cm) at bases of sets and foresets; variable cementation; DEFORMED SANDSTONE bedding (between 2.0 and 3.5 m) might have resulted from deposition of overlaying beds

CITY/TOWN: Tabuk - Bajdah

SECTION: T104 (1 PAGE)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 06.004′, E 35° 59.072′



DESCRIPTION / REMARKS

(THINLY-BEDDED) SIGMOIDAL CROSS-BEDDED SANDSTONE: orange to reddish-brown; medium (l)- to coarse (u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; (thinly-bedded) sigmoidal cross-bedded sets (15-40 cm thick); some sets show bundled-foresets; fining-upward trend, locally into maroon, silty to argillaceous FLAT-LAMINATED SANDSTONE beds; random inclusions of pebble-size quartz (up to 3 cm in size); lags show concentrations of pebble-size quartz (up to 3 cm in size); one bed shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS

(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: orange to reddish-brown; medium (l)- to coarse (l)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; (pebbly) trough cross-bedded sets (15-30 cm thick; up to 5 m wide); shows concentrations of sand- to pebble-size quartz at bases of foresets; fining-upward trend, locally into very fine (l)-grained to silty FLAT-LAMINATED TO MASSIVE SANDSTONE; one trough cross-bedded set is found adjacent to flat-laminated to massive sandstone bed, topped by DEFORMED SANDSTONE beds

PLANAR TABULAR CROSS-BEDDED SANDSTONE: orange to reddish-brown; coarse (u)-grained; moderately- to poorly-sorted; sub-angular to well-rounded; planar tabular cross-bedded set (up to 150 cm thick); shows concentrations of sand- to pebble-size quartz at bases of foresets; underlying lag shows well-rounded quartz pebbles (up to 5 cm in size); top of set shows overturning

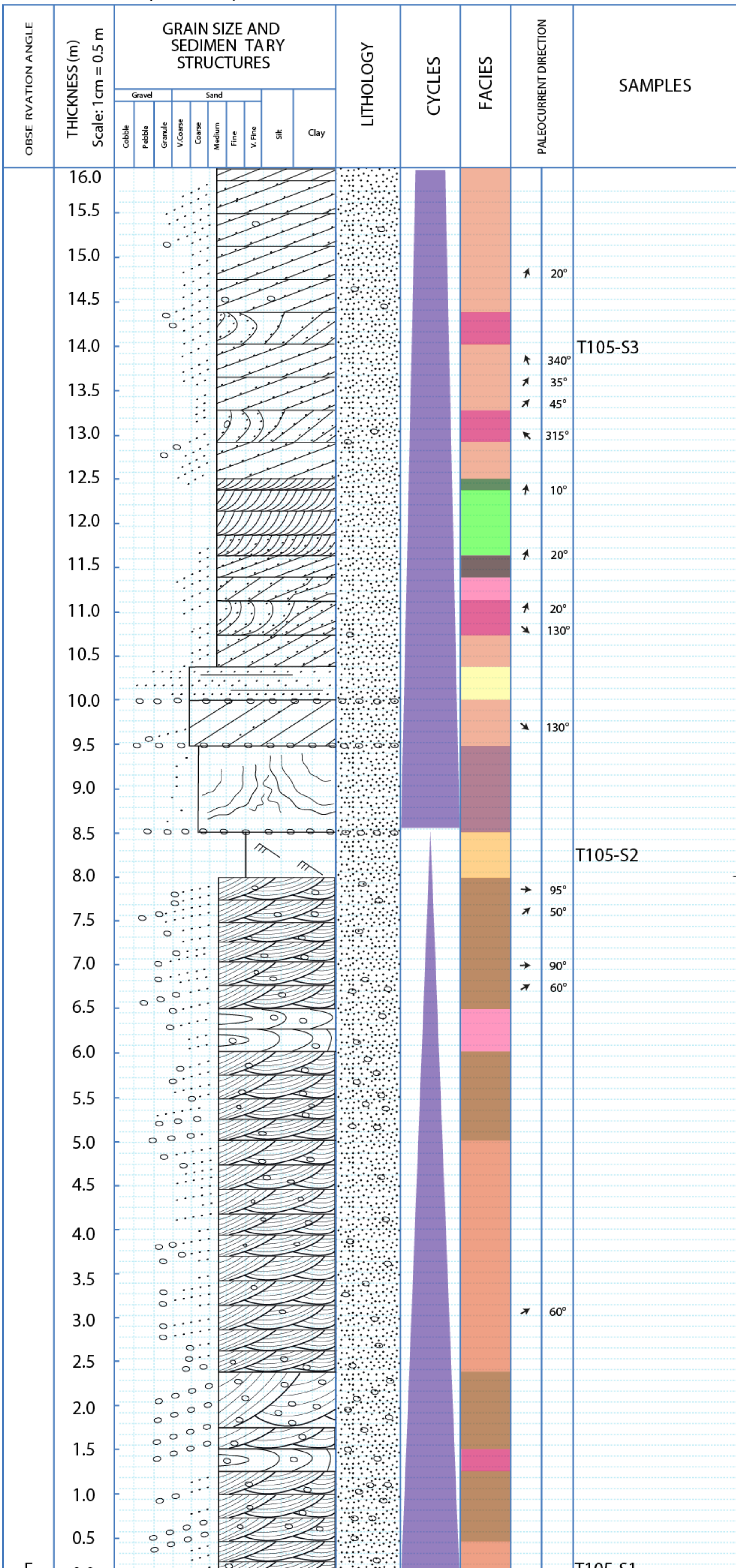
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: reddish-brown; medium (l)- to coarse (l)-grained; moderately- to poorly-sorted; angular to sub-rounded; (pebbly) trough cross-bedded sets (20-30 cm thick; up to 5 m wide); show of concentrations of sand- to pebble-size quartz (up to 7 cm in size) and rare granitic fragments (up to 6 cm in size) at bases of sets and foresets; evidence of soft sediment deformation (observed at ~ 1.0 m)

CITY/TOWN: Tabuk - Bajdah

SECTION: T105 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 07.200′, E 36° 00.816′



DESCRIPTION / REMARKS

PLANAR TABULAR CROSS-BEDDED SANDSTONE: orange to reddish-brown (weathering); medium (u)-grained; moderately-sorted; sub- to well-rounded; planar tabular cross-bedded sets (10-30 cm thick); shows concentrations of sand- to pebble-size quartz (up to 3 cm in size; mostly well-rounded) at bases of foresets; beddings shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

PLANAR TABULAR CROSS-BEDDED SANDSTONE: orange to reddish-brown (weathering); medium (u) to very coarse (l)-grained; well- to moderately-sorted; sub- to well-rounded; planar tabular cross-bedded sets (20-50 cm thick); concentrations of coarser-sand grains are observed at bases of foresets; fining-upward trend uppermost sets develops (THINLY-BEDDED) TANGENTIAL CROSS-BEDDED SANDSTONE (<10-20 cm thick); recurring lags show concentrations of sand- to pebble-size quartz; one set shows MASSIVE SANDSTONE bed; bedding displays DEFORMED SANDSTONE, INTENSELY-DEFORMED SANDSTONE (fluid escape structure) and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

RIPPLE-LAMINATED SANDSTONE: white to purple and grey (weathering); fine (l)-grained; well- to moderately-sorted; sub- to well-rounded; ripple-laminated sandstone bed

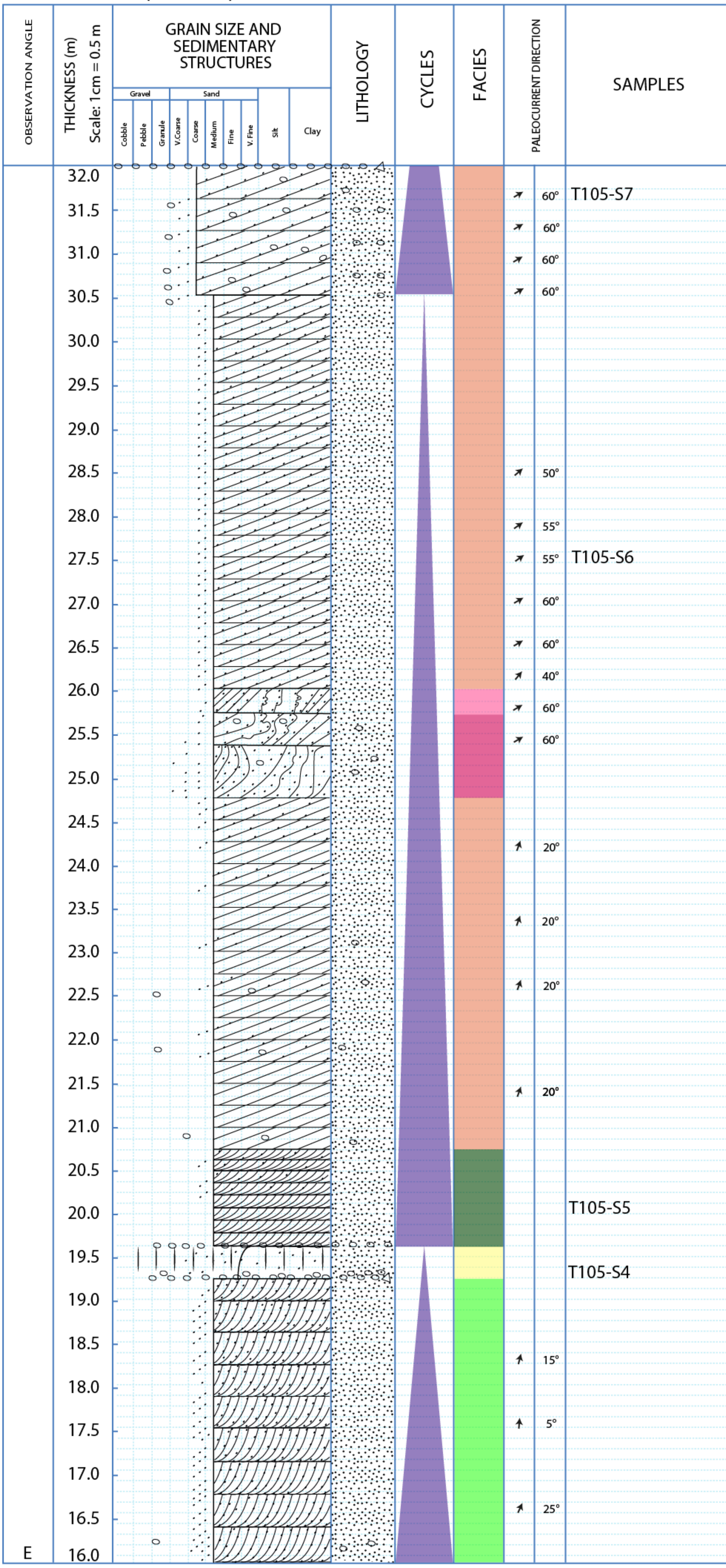
(PEBBLY) TROUGH CROSS-BEDDED SANDSTONE: white to purple (weathering); medium (u)-grained; moderately- to poorly-sorted; sub-angular to sub-rounded; (pebbly) trough cross-bedded sets (10-70 cm thick); shows concentrations of sand- to pebble-size well-rounded quartz at bases of foresets; bedding shows CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS beds

CITY/TOWN: Tabuk - Bajdah

SECTION: T105 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 07.200′, E 36° 00.816′



DESCRIPTION / REMARKS

PLANAR TABULAR CROSS-BEDDED SANDSTONE: tan to reddish-brown (weathering); medium (u) to coarse (u)-grained; moderately-sorted; sub-angular to sub-rounded; planar tabular cross-bedded sets (10-40 cm thick); shows concentrations of sand- to pebble-size quartz (up to 5 cm in size) at bases of foresets; lags show concentrations of pebble-size quartz and rare granitic fragments; two beds show DEFORMED SANDSTONE and CROSS-BEDDED SANDSTONE WITH OVERTURNED FORESETS

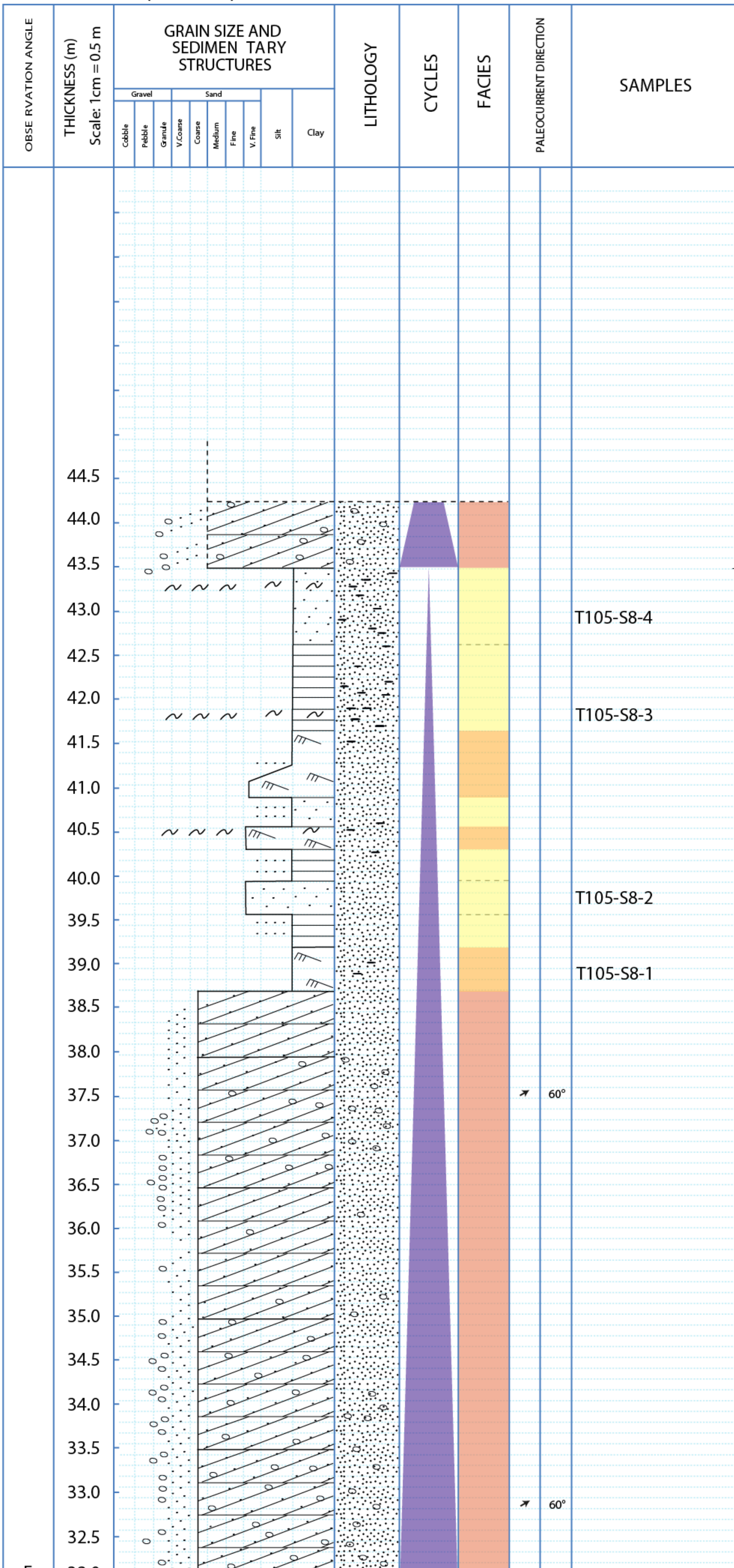
(THINLY-BEDDED) TANGENTIAL CROSS-BEDDED SANDSTONE: orange to reddish-brown (weathering); medium (u)-grained; moderately-sorted; sub-angular to sub-rounded; (thinly-bedded) tangential cross-bedded sets (<10-30 cm thick); shows concentrations of coarser-sand grains at bases of foresets; recurring lags show concentrations of sand- to pebble-size quartz (up to 4 cm in size; well-rounded and elongated) and rare granitic fragments; one set (at ~ 19.5 m), bounded by two lags show MASSIVE SANDSTONE beds with intensive burrowing (*Skolithos*; up to 7 cm in length)

CITY/TOWN: Tabuk - Bajdah

SECTION: T105 (3 PAGES)

NAME: ABDULLAH WAHBI

LOCATION: N 28° 07.200′, E 36° 00.816′



DESCRIPTION / REMARKS

PLANAR TABULAR CROSS-BEDDED SANDSTONE: tan to reddish-brown (weathering); coarse (l)-grained; moderately-sorted; sub-angular to sub-rounded; planar tabular cross-bedded sets (20-30 cm thick); concentrations of sand- to pebble-size quartz (up to 5 cm in size) at bases of foresets

RIPPLE- AND FLAT-LAMINATED TO MASSIVE SANDSTONE: white, buff, maroon and dark purple (weathering); silty to very fine (u)-grained; argillaceous in places; well-sorted (bimodally-sorted in places); well-rounded; ripple- to flat-laminated sandstone beds (rare lenticular-laminated beds); *Cruziana* trace fossils found in float

PLANAR TABULAR CROSS-BEDDED SANDSTONE: tan to reddish-brown (weathering); coarse (u)-grained; moderately-sorted; sub-angular to sub-rounded; planar tabular cross-bedded sets (20-30 cm thick); shows concentrations of sand- to pebble-size quartz (up to 5 cm in size) at bases of foresets; lag shows concentrations of pebble-size quartz and rare granitic fragments

FACIES DISTRIBUTIONS

Table 3: Measured footage of depositional facies per location, study area, measured section and sandstone unit.

Location	Area	Measured Section	Sandstone Unit	Facies Measurement (cm)															Total	Grand Total
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	Missing		
Al Ula	U1	U101	L. Siq	0	0	0	0	0	700	200	0	0	0	0	100	150	0	0	1150	
Al Ula	U1	U101	M. Siq	0	0	1050	1675	450	1050	175	250	375	1225	0	0	0	0	0	6250	7400
Al Ula	U1	U102	M. Siq	0	0	375	0	0	50	50	50	75	600	0	75	0	0	0	1275	
Al Ula	U1	U102	U. Siq	0	0	300	1150	0	0	75	0	75	325	0	0	0	0	100	2025	
Al Ula	U1	U102	Quweira	0	300	325	25	0	25	50	0	0	100	0	25	0	0	0	850	4150
Al Ula	U1	U103	Quweira	0	150	700	1225	500	0	250	0	25	275	0	0	0	0	75	3200	3200
Al Ula	U2	U201	Quweira	0	0	0	1200	225	0	1000	0	25	325	25	50	0	0	0	2850	2850
Al Ula	U2	U202a	Quweira	0	400	425	725	25	500	175	0	0	0	475	150	0	0	0	2875	2875
Al Ula	U2	U202b	Quweira	0	0	75	350	0	650	300	0	25	25	0	25	50	0	0	1500	1500
Al Ula	U3	U301	U. Siq	0	0	1250	975	0	0	0	0	225	250	50	50	0	0	0	2800	2800
Al Ula	U3	U302	U. Siq	0	0	0	25	0	0	0	0	50	100	0	0	0	0	0	175	
Al Ula	U3	U302	Quweira	0	150	1250	1925	500	100	0	0	125	25	0	100	0	0	0	4175	4350
Al Ula	U3	U303	Quweira	0	0	425	2250	75	100	100	0	0	50	75	125	0	0	0	3200	3200
Al Ula	U3	U304	Quweira	0	0	350	1675	0	0	0	0	0	0	125	100	0	0	0	2250	2250
Al Ula	U3	U305	Quweira	400	50	975	3350	0	0	75	0	100	225	500	175	0	0	0	5850	5850
Al Ula	U4	U401	Quweira	50	0	1025	3450	0	250	175	50	125	325	250	250	0	0	0	5950	5950
Al Ula	U5	U501a	Saq	0	0	25	175	0	0	50	0	0	0	100	25	0	0	0	375	375
Al Ula	U5	U501b	Saq	0	0	100	1075	150	25	0	0	50	75	100	25	0	0	0	1600	1600
Al Ula	U5	U502	Saq	0	0	125	75	0	200	300	0	50	25	925	100	50	0	0	1850	1850
Tabuk	T1	T101	U. Siq	0	0	25	425	0	375	0	0	100	375	175	175	0	0	0	1650	
Tabuk	T1	T101	Quweira	0	0	0	0	0	675	275	0	0	50	175	75	0	0	0	1250	2900
Tabuk	T1	T102	Quweira	0	0	0	450	0	525	0	0	0	0	225	125	75	0	0	1400	1400
Tabuk	T1	T103a	Quweira	0	0	0	250	0	0	0	0	0	0	0	0	150	0	0	400	400
Tabuk	T1	T103b	Quweira	0	0	0	225	0	125	150	0	0	0	275	50	0	775	0	1600	1600
Tabuk	T1	T104	Quweira	0	0	400	225	150	350	50	0	0	50	50	25	0	0	0	1300	1300
Tabuk	T1	T105	Quweira	0	0	425	300	0	0	0	0	50	0	0	75	0	0	0	850	
Tabuk	T1	T105	Saq	0	0	0	0	2025	400	150	0	150	500	50	200	100	0	0	3575	4425
Total (cm)																			**62225**	

PALEOCURRENT DIRECTION DATA

Table 4: Paleocurrent direction data collected from cross-bedded sandstone facies in both the Al Ula and Tabuk study areas from all areas, measured sections and sandstone units.

#	Location	Area	Measured Section	Sandstone Uni	Facies	Height (m)	Measurement (degrees)
1	Al Ula	U1	U101	L.Siq	6	8.5	330
2	Al Ula	U1	U101	L.Siq	7	10.0	330
3	Al Ula	U1	U101	M.Siq	3	12.0	330
4	Al Ula	U1	U101	M.Siq	3	13.0	325
5	Al Ula	U1	U101	M.Siq	3	13.0	310
6	Al Ula	U1	U101	M.Siq	3	13.0	335
7	Al Ula	U1	U101	M.Siq	3	13.0	295
8	Al Ula	U1	U101	M.Siq	3	13.5	280
9	Al Ula	U1	U101	M.Siq	3	14.0	15
10	Al Ula	U1	U101	M.Siq	4	14.5	20
11	Al Ula	U1	U101	M.Siq	4	15.5	25
12	Al Ula	U1	U101	M.Siq	4	16.5	330
13	Al Ula	U1	U101	M.Siq	5	19.5	350
14	Al Ula	U1	U101	M.Siq	5	21.0	340
15	Al Ula	U1	U101	M.Siq	10	26.5	350
16	Al Ula	U1	U101	M.Siq	4	32.5	330
17	Al Ula	U1	U101	M.Siq	4	33.5	345
18	Al Ula	U1	U101	M.Siq	4	46.5	80
19	Al Ula	U1	U103	Quweira	3	0.0	0
20	Al Ula	U1	U103	Quweira	5	1.0	330
21	Al Ula	U1	U103	Quweira	3	2.5	0
22	Al Ula	U1	U103	Quweira	3	3.5	330
23	Al Ula	U1	U103	Quweira	5	4.5	0
24	Al Ula	U1	U103	Quweira	3	5.0	30
25	Al Ula	U1	U103	Quweira	3	10.0	325
26	Al Ula	U1	U103	Quweira	4	13.0	330
27	Al Ula	U1	U103	Quweira	4	30.5	15
28	Al Ula	U1	U103	Quweira	7	31.5	335
29	Al Ula	U2	U201	Quweira	4	0.5	350
30	Al Ula	U2	U201	Quweira	4	0.5	345
31	Al Ula	U2	U201	Quweira	4	1.5	350
32	Al Ula	U2	U201	Quweira	4	2.0	355
33	Al Ula	U2	U201	Quweira	5	3.0	320
34	Al Ula	U2	U201	Quweira	5	3.5	320
35	Al Ula	U2	U201	Quweira	4	5.5	90
36	Al Ula	U2	U201	Quweira	4	6.0	70
37	Al Ula	U2	U201	Quweira	7	7.0	0
38	Al Ula	U2	U201	Quweira	4	7.0	40
39	Al Ula	U2	U201	Quweira	4	7.5	30
40	Al Ula	U2	U201	Quweira	4	7.5	45
41	Al Ula	U2	U201	Quweira	7	8.0	0
42	Al Ula	U2	U202a	Quweira	11	0.0	225
43	Al Ula	U2	U202a	Quweira	11	0.0	0
44	Al Ula	U2	U202a	Quweira	11	1.0	40
45	Al Ula	U2	U202a	Quweira	3	4.0	100
46	Al Ula	U2	U202a	Quweira	11	6.0	15
47	Al Ula	U2	U202a	Quweira	3	9.0	125
48	Al Ula	U2	U202a	Quweira	11	10.0	270
49	Al Ula	U2	U202a	Quweira	11	10.0	270
50	Al Ula	U2	U202a	Quweira	2	10.5	340
51	Al Ula	U2	U202a	Quweira	2	11.0	340
52	Al Ula	U2	U202a	Quweira	2	12.0	340
53	Al Ula	U2	U202a	Quweira	4	13.0	20
54	Al Ula	U2	U202a	Quweira	4	25.5	15
55	Al Ula	U2	U202a	Quweira	4	25.5	5

#	Location	Area	Measured Section	Sandstone Uni	Facies	Height (m)	Measurement (degrees)
56	Al Ula	U2	U202a	Quweira	4	25.5	0
57	Al Ula	U2	U202a	Quweira	4	25.5	5
58	Al Ula	U2	U202b	Quweira	4	1.5	30
59	Al Ula	U2	U202b	Quweira	4	5.5	330
60	Al Ula	U2	U202b	Quweira	4	5.5	10
61	Al Ula	U2	U202b	Quweira	4	6.0	30
62	Al Ula	U2	U202b	Quweira	7	10.0	0
63	Al Ula	U3	U301	U.Siq	3	2.5	30
64	Al Ula	U3	U301	U.Siq	3	3.0	30
65	Al Ula	U3	U301	U.Siq	3	3.5	20
66	Al Ula	U3	U301	U.Siq	3	11.5	330
67	Al Ula	U3	U303	Quweira	4	0.0	0
68	Al Ula	U3	U303	Quweira	4	0.5	10
69	Al Ula	U3	U303	Quweira	4	0.5	15
70	Al Ula	U3	U303	Quweira	4	0.5	30
71	Al Ula	U3	U303	Quweira	4	3.0	25
72	Al Ula	U3	U303	Quweira	4	6.0	55
73	Al Ula	U3	U303	Quweira	3	7.0	85
74	Al Ula	U3	U303	Quweira	3	19.0	15
75	Al Ula	U3	U303	Quweira	3	19.5	15
76	Al Ula	U3	U303	Quweira	3	20.0	35
77	Al Ula	U3	U303	Quweira	4	22.5	10
78	Al Ula	U3	U304	Quweira	4	21.0	330
79	Al Ula	U3	U304	Quweira	4	21.5	20
80	Al Ula	U3	U304	Quweira	4	22.0	30
81	Al Ula	U3	U304	Quweira	4	22.5	325
82	Al Ula	U3	U305	Quweira	7	0.0	65
83	Al Ula	U3	U305	Quweira	7	0.5	80
84	Al Ula	U3	U305	Quweira	7	0.5	55
85	Al Ula	U3	U305	Quweira	7	0.5	30
86	Al Ula	U3	U305	Quweira	4	5.0	0
87	Al Ula	U3	U305	Quweira	4	5.5	30
88	Al Ula	U3	U305	Quweira	4	5.5	45
89	Al Ula	U3	U305	Quweira	4	6.0	20
90	Al Ula	U3	U305	Quweira	4	6.5	350
91	Al Ula	U3	U305	Quweira	3	6.5	0
92	Al Ula	U3	U305	Quweira	3	11.5	15
93	Al Ula	U3	U305	Quweira	3	11.5	15
94	Al Ula	U3	U305	Quweira	3	11.5	25
95	Al Ula	U3	U305	Quweira	3	11.5	30
96	Al Ula	U3	U305	Quweira	3	11.5	30
97	Al Ula	U3	U305	Quweira	3	11.5	40
98	Al Ula	U3	U305	Quweira	3	11.5	45
99	Al Ula	U3	U305	Quweira	1	18.5	20
100	Al Ula	U3	U305	Quweira	1	19.0	20
101	Al Ula	U3	U305	Quweira	1	19.5	20
102	Al Ula	U3	U305	Quweira	1	20.0	20
103	Al Ula	U3	U305	Quweira	1	20.5	20
104	Al Ula	U3	U305	Quweira	1	21.0	20
105	Al Ula	U3	U305	Quweira	11	23.0	35
106	Al Ula	U3	U305	Quweira	10	58.0	100
107	Al Ula	U3	U305	Quweira	10	58.5	160
108	Al Ula	U4	U401	Quweira	4	0.0	325
109	Al Ula	U4	u401	Quweira	4	8.5	65
110	Al Ula	U4	U401	Quweira	4	8.5	90

#	Location	Area	Measured Section	Sandstone Uni	Facies	Height (m)	Measurement (degrees)
111	Al Ula	U4	U401	Quweira	4	8.5	80
112	Al Ula	U4	U401	Quweira	4	8.5	40
113	Al Ula	U4	U401	Quweira	4	8.5	25
114	Al Ula	U4	U401	Quweira	4	8.5	80
115	Al Ula	U4	U401	Quweira	4	8.5	65
116	Al Ula	U4	U401	Quweira	4	8.5	45
117	Al Ula	U4	U401	Quweira	4	8.5	90
118	Al Ula	U4	U401	Quweira	4	14.5	35
119	Al Ula	U4	U401	Quweira	4	24.5	345
120	Al Ula	U4	U401	Quweira	4	24.5	0
121	Al Ula	U4	U401	Quweira	4	24.5	335
122	Al Ula	U4	U401	Quweira	4	24.5	15
123	Al Ula	U4	U401	Quweira	4	24.5	345
124	Al Ula	U5	U501a	Saq	4	0.0	30
125	Al Ula	U5	U501a	Saq	3	0.5	30
126	Al Ula	U5	U501a	Saq	4	1.0	0
127	Al Ula	U5	U501a	Saq	7	4.0	45
128	Al Ula	U5	U501b	Saq	11	0.0	35
129	Al Ula	U5	U501b	Saq	11	0.0	20
130	Al Ula	U5	U501b	Saq	11	0.0	25
131	Al Ula	U5	U501b	Saq	11	0.0	30
132	Al Ula	U5	U501b	Saq	11	0.0	60
133	Al Ula	U5	U501b	Saq	11	0.0	65
134	Al Ula	U5	U501b	Saq	10	13.0	60
135	Al Ula	U5	U502	Saq	3	0.5	35
136	Al Ula	U5	U502	Saq	3	0.5	35
137	Al Ula	U5	U502	Saq	3	0.5	35
138	Al Ula	U5	U502	Saq	3	0.5	35
139	Al Ula	U5	U502	Saq	3	2.5	80
140	Al Ula	U5	U502	Saq	3	2.5	90
141	Al Ula	U5	U502	Saq	3	3.0	95

PETROGRAPHIC DATA

Table 5: Point-count petrographic data collected from thin sections of Tabuk and Al Ula study areas.

#	Count	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Section	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101	U101
	Sample	S1	S2	S3	S4	S5	S6	S7	S7-1	S7-2	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18
1	Monocrystalline Quartz	101	138	108	95	85	77	116	110	87	131	160	120	99	102	111	140	150	68	99	118
2	Polycrystalline Quartz	11	3	2	5	4	4	10	21	1	18	30	26	2	18	5	2	1	0	1	2
3	Potassium Feldspars	39	41	30	35	7	9	33	17	14	16	3	9	3	15	5	14	14	7	6	41
4	Plagioclase	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	2	0	2	0	0
5	Lithics	55	52	67	81	102	104	33	70	72	50	41	45	58	73	67	40	42	10	83	57
6	Matrix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150		0
7	Muscovite	0	0	5	3	3	4	2	1	1	2	0	0	0	0	0	1	1	2	1	0
8	Kaolinite	1	1	1	0	1	6	3	0	0	0	1	0	2	0	1	3	0	0	0	0
9	Iron Oxide	62	19	42	15	23	53	37	44	77	12	12	4	84	30	42	14	5	19	13	14
10	Quartz Overgrowth	0	0	0	0	2	0	0	0	0	4	0	0	0	3	4	0	0	0	0	5
11	Intergranular Porosity	24	40	29	50	53	24	55	19	39	58	38	88	44	53	56	65	69	22	77	52
12	Intragranular Porosity	7	6	15	16	19	19	10	18	9	9	15	8	8	6	9	19	18	20	20	11
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	Monocrystalline Quartz	33.67%	46.00%	36.00%	31.67%	28.33%	25.67%	38.67%	36.67%	29.00%	43.67%	53.33%	40.00%	33.00%	34.00%	37.00%	46.67%	50.00%	22.67%	33.00%	39.33%
2	Polycrystalline Quartz	3.67%	1.00%	0.67%	1.67%	1.33%	1.33%	3.33%	7.00%	0.33%	6.00%	10.00%	8.67%	0.67%	6.00%	1.67%	0.67%	0.33%	0.00%	0.33%	0.67%
3	Potassium Feldspars	13.00%	13.67%	10.00%	11.67%	2.33%	3.00%	11.00%	5.67%	4.67%	5.33%	1.00%	3.00%	1.00%	5.00%	1.67%	4.67%	4.67%	2.33%	2.00%	13.67%
4	Plagioclase	0.00%	0.00%	0.33%	0.00%	0.33%	0.00%	0.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.67%	0.00%	0.67%	0.00%	0.00%
5	Lithics	18.33%	17.33%	22.33%	27.00%	34.00%	34.67%	11.00%	23.33%	24.00%	16.67%	13.67%	15.00%	19.33%	24.33%	22.33%	13.33%	14.00%	3.33%	27.67%	19.00%
6	Matrix	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	50.00%	0.00%	0.00%
7	Muscovite	0.00%	0.00%	1.67%	1.00%	1.00%	1.33%	0.67%	0.33%	0.33%	0.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.33%	0.67%	0.33%	0.00%
8	Kaolinite	0.33%	0.33%	0.33%	0.00%	0.33%	2.00%	1.00%	0.00%	0.00%	0.00%	0.33%	0.00%	0.67%	0.00%	0.33%	1.00%	0.00%	0.00%	0.00%	0.00%
9	Iron Oxide	20.67%	6.33%	14.00%	5.00%	7.67%	17.67%	12.33%	14.67%	25.67%	4.00%	4.00%	1.33%	28.00%	10.00%	14.00%	4.67%	1.67%	6.33%	4.33%	4.67%
10	Quartz Overgrowth	0.00%	0.00%	0.00%	0.00%	0.67%	0.00%	0.00%	0.00%	0.00%	1.33%	0.00%	0.00%	0.00%	1.00%	1.33%	0.00%	0.00%	0.00%	0.00%	1.67%
11	Intergranular Porosity	8.00%	13.33%	9.67%	16.67%	17.67%	8.00%	18.33%	6.33%	13.00%	19.33%	12.67%	29.33%	14.67%	17.67%	18.67%	21.67%	23.00%	7.33%	25.67%	17.33%
12	Intragranular Porosity	2.33%	2.00%	5.00%	5.33%	6.33%	6.33%	3.33%	6.00%	3.00%	3.00%	5.00%	2.67%	2.67%	2.00%	3.00%	6.33%	6.00%	6.67%	6.67%	3.67%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	10.33%	15.33%	14.67%	22.00%	24.00%	14.33%	21.67%	12.33%	16.00%	22.33%	17.67%	32.00%	17.33%	19.67%	21.67%	28.00%	29.00%	14.00%	32.33%	21.00%
	QFL Count	206	234	208	216	199	194	193	218	174	215	234	200	162	208	188	198	207	87	189	218
1	Quartz	112	141	110	100	89	81	126	131	88	149	190	146	101	120	116	142	151	68	100	120
2	Feldspars	39	41	31	35	8	9	34	17	14	16	3	9	3	15	5	16	14	9	6	41
3	Lithics	55	52	67	81	102	104	33	70	72	50	41	45	58	73	67	40	42	10	83	57
1	Quartz	54.37%	60.26%	52.88%	46.30%	44.72%	41.75%	65.28%	60.09%	50.57%	69.30%	81.20%	73.00%	62.35%	57.69%	61.70%	71.72%	72.95%	78.16%	52.91%	55.05%
2	Feldspars	18.93%	17.52%	14.90%	16.20%	4.02%	4.64%	17.62%	7.80%	8.05%	7.44%	1.28%	4.50%	1.85%	7.21%	2.66%	8.08%	6.76%	10.34%	3.17%	18.81%
3	Lithics	26.70%	22.22%	32.21%	37.50%	51.26%	53.61%	17.10%	32.11%	41.38%	23.26%	17.52%	22.50%	35.80%	35.10%	35.64%	20.20%	20.29%	11.49%	43.92%	26.15%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	Section	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U102	U103	U103	U103
	Sample	S1	S1-1	S2	S2-1	S3	S4	S4-1	S4-2	S5	S5-1	S5-2	S6	S7	S8	S8-1	S9	S9-1	S1	S1-1	S1-2
1	Monocrystalline Quartz	113	156	171	140	115	101	180	179	125	130	92	134	154	171	174	120	161	175	179	180
2	Polycrystalline Quartz	3	5	2	4	3	6	10	3	9	10	1	6	2	8	11	1	11	10	27	1
3	Potassium Feldspars	4	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	Plagioclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Lithics	64	62	30	74	89	69	23	21	46	54	120	66	56	31	26	38	47	24	19	11
6	Matrix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Muscovite	0	0	0	4	5	2	0	0	1	1	2	2	0	3	3	10	0	0	0	0
8	Kaolinite	0	0	0	1	2	3	0	0	1	0	6	3	0	0	0	18	0	0	3	1
9	Iron Oxide	30	28	53	53	43	88	16	42	67	71	54	9	38	4	28	112	10	8	8	4
10	Quartz Overgrowth	3	0	4	4	5	6	20	9	13	11	3	17	7	19	14	1	20	36	17	9
11	Intergranular Porosity	80	43	38	15	35	21	43	43	35	18	15	48	31	61	41	0	44	47	46	94
12	Intragranular Porosity	3	6	2	5	2	3	8	2	2	5	7	15	12	3	3	0	7	0	1	0
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	Monocrystalline Quartz	37.67%	52.00%	57.00%	46.67%	38.33%	33.67%	60.00%	59.67%	41.67%	43.33%	30.67%	44.67%	51.33%	57.00%	58.00%	40.00%	53.67%	58.33%	59.67%	60.00%
2	Polycrystalline Quartz	1.00%	1.67%	0.67%	1.33%	1.00%	2.00%	3.33%	1.00%	3.00%	3.33%	0.33%	2.00%	0.67%	2.67%	3.67%	0.33%	3.67%	3.33%	9.00%	0.33%
3	Potassium Feldspars	1.33%	0.00%	0.00%	0.00%	0.33%	0.33%	0.00%	0.33%	0.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	Plagioclase	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	Lithics	21.33%	20.67%	10.00%	24.67%	29.67%	23.00%	7.67%	7.00%	15.33%	18.00%	40.00%	22.00%	18.67%	10.33%	8.67%	12.67%	15.67%	8.00%	6.33%	3.67%
6	Matrix	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	Muscovite	0.00%	0.00%	0.00%	1.33%	1.67%	0.67%	0.00%	0.00%	0.33%	0.33%	0.67%	0.67%	0.00%	1.00%	1.00%	3.33%	0.00%	0.00%	0.00%	0.00%
8	Kaolinite	0.00%	0.00%	0.00%	0.33%	0.67%	1.00%	0.00%	0.00%	0.33%	0.00%	2.00%	1.00%	0.00%	0.00%	0.00%	6.00%	0.00%	0.00%	1.00%	0.33%
9	Iron Oxide	10.00%	9.33%	17.67%	17.67%	14.33%	29.33%	5.33%	14.00%	22.33%	23.67%	18.00%	3.00%	12.67%	1.33%	9.33%	37.33%	3.33%	2.67%	2.67%	1.33%
10	Quartz Overgrowth	1.00%	0.00%	1.33%	1.33%	1.67%	2.00%	6.67%	3.00%	4.33%	3.67%	1.00%	5.67%	2.33%	6.33%	4.67%	0.33%	6.67%	12.00%	5.67%	3.00%
11	Intergranular Porosity	26.67%	14.33%	12.67%	5.00%	11.67%	7.00%	14.33%	14.33%	11.67%	6.00%	5.00%	16.00%	10.33%	20.33%	13.67%	0.00%	14.67%	15.67%	15.33%	31.33%
12	Intragranular Porosity	1.00%	2.00%	0.67%	1.67%	0.67%	1.00%	2.67%	0.67%	0.67%	1.67%	2.33%	5.00%	4.00%	1.00%	1.00%	0.00%	2.33%	0.00%	0.33%	0.00%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	27.67%	16.33%	13.33%	6.67%	12.33%	8.00%	17.00%	15.00%	12.33%	7.67%	7.33%	21.00%	14.33%	21.33%	14.67%	0.00%	17.00%	15.67%	15.67%	31.33%
	QFL Count	184	223	203	218	208	177	213	204	181	194	213	206	212	210	211	159	219	209	225	192
1	Quartz	116	161	173	144	118	107	190	182	134	140	93	140	156	179	185	121	172	185	206	181
2	Feldspars	4	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
3	Lithics	64	62	30	74	89	69	23	21	46	54	120	66	56	31	26	38	47	24	19	11
1	Quartz	63.04%	72.20%	85.22%	66.06%	56.73%	60.45%	89.20%	89.22%	74.03%	72.16%	43.66%	67.96%	73.58%	85.24%	87.68%	76.10%	78.54%	88.52%	91.56%	94.27%
2	Feldspars	2.17%	0.00%	0.00%	0.00%	0.48%	0.56%	0.00%	0.49%	0.55%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	Lithics	34.78%	27.80%	14.78%	33.94%	42.79%	38.98%	10.80%	10.29%	25.41%	27.84%	56.34%	32.04%	26.42%	14.76%	12.32%	23.90%	21.46%	11.48%	8.44%	5.73%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	Section	U103	U103	U103	U103	U103	U103	U301	U301	U301	U301	U301	U301	U301	U301	U301	U302	U302	U302	U302	U302
	Sample	S2	S3	S4	S4-1	S5	S6	S1	S2	S3	S4	S4-1	S5	S6	S7	S8	S1	S2	S3	S4	S5
1	**Monocrystalline Quartz**	155	136	134	106	155	185	96	104	141	79	138	115	116	75	61	103	129	128	164	145
2	**Polycrystalline Quartz**	7	5	1	20	13	7	2	2	5	4	1	1	0	0	2	4	10	3	9	9
3	**Potassium Feldspars**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	**Plagioclase**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	**Lithics**	34	45	63	77	19	24	109	93	67	141	94	49	76	94	140	122	69	89	47	52
6	**Matrix**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	**Muscovite**	0	1	0	1	0	0	1	2	1	1	0	1	1	1	5	1	0	0	2	0
8	**Kaolinite**	2	5	5	3	4	0	0	0	1	3	0	15	0	4	2	0	2	0	7	1
9	**Iron Oxide**	33	96	62	55	93	15	53	63	42	51	43	119	33	86	75	31	15	59	30	49
10	**Quartz Overgrowth**	15	12	12	12	16	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	**Intergranular Porosity**	48	0	16	19	0	49	22	24	27	6	13	0	51	29	6	14	62	13	28	31
12	**Intragranular Porosity**	6	0	7	7	0	9	17	12	16	15	11	0	23	11	9	25	13	8	13	13
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	**Monocrystalline Quartz**	51.67%	45.33%	44.67%	35.33%	51.67%	61.67%	32.00%	34.67%	47.00%	26.33%	46.00%	38.33%	38.67%	25.00%	20.33%	34.33%	43.00%	42.67%	54.67%	48.33%
2	**Polycrystalline Quartz**	2.33%	1.67%	0.33%	6.67%	4.33%	2.33%	0.67%	0.67%	1.67%	1.33%	0.33%	0.33%	0.00%	0.00%	0.67%	1.33%	3.33%	1.00%	3.00%	3.00%
3	**Potassium Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	**Plagioclase**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	**Lithics**	11.33%	15.00%	21.00%	25.67%	6.33%	8.00%	36.33%	31.00%	22.33%	47.00%	31.33%	16.33%	25.33%	31.33%	46.67%	40.67%	23.00%	29.67%	15.67%	17.33%
6	**Matrix**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	**Muscovite**	0.00%	0.33%	0.00%	0.33%	0.00%	0.00%	0.33%	0.67%	0.33%	0.33%	0.00%	0.33%	0.33%	0.33%	1.67%	0.33%	0.00%	0.00%	0.67%	0.00%
8	**Kaolinite**	0.67%	1.67%	1.67%	1.00%	1.33%	0.00%	0.00%	0.00%	0.33%	1.00%	0.00%	5.00%	0.00%	1.33%	0.67%	0.00%	0.67%	0.00%	2.33%	0.33%
9	**Iron Oxide**	11.00%	32.00%	20.67%	18.33%	31.00%	5.00%	17.67%	21.00%	14.00%	17.00%	14.33%	39.67%	11.00%	28.67%	25.00%	10.33%	5.00%	19.67%	10.00%	16.33%
10	**Quartz Overgrowth**	5.00%	4.00%	4.00%	4.00%	5.33%	3.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
11	**Intergranular Porosity**	16.00%	0.00%	5.33%	6.33%	0.00%	16.33%	7.33%	8.00%	9.00%	2.00%	4.33%	0.00%	17.00%	9.67%	2.00%	4.67%	20.67%	4.33%	9.33%	10.33%
12	**Intragranular Porosity**	2.00%	0.00%	2.33%	2.33%	0.00%	3.00%	5.67%	4.00%	5.33%	5.00%	3.67%	0.00%	7.67%	3.67%	3.00%	8.33%	4.33%	2.67%	4.33%	4.33%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	18.00%	0.00%	7.67%	8.67%	0.00%	19.33%	13.00%	12.00%	14.33%	7.00%	8.00%	0.00%	24.67%	13.33%	5.00%	13.00%	25.00%	7.00%	13.67%	14.67%
	QFL Count	196	186	198	203	187	216	207	199	213	224	233	165	192	169	203	229	208	220	220	206
1	**Quartz**	162	141	135	126	168	192	98	106	146	83	139	116	116	75	63	107	139	131	173	154
2	**Feldspars**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	**Lithics**	34	45	63	77	19	24	109	93	67	141	94	49	76	94	140	122	69	89	47	52
1	**Quartz**	82.65%	75.81%	68.18%	62.07%	89.84%	88.89%	47.34%	53.27%	68.54%	37.05%	59.66%	70.30%	60.42%	44.38%	31.03%	46.72%	66.83%	59.55%	78.64%	74.76%
2	**Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	**Lithics**	17.35%	24.19%	31.82%	37.93%	10.16%	11.11%	52.66%	46.73%	31.46%	62.95%	40.34%	29.70%	39.58%	55.62%	68.97%	53.28%	33.17%	40.45%	21.36%	25.24%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
	Section	U302	U302	U302	U302	U302	U302	U302	U303	U303	U303	U303	U303	U303	U304	U304	U304	U305	U305	U305	U305
	Sample	S6	S7	S8	S9	S10	S11	S12	S1	S2	S3	S4	S5	S6	S1	S2	S3	S1	S2	S3	S4
1	**Monocrystalline Quartz**	115	156	142	152	162	147	158	198	174	167	151	158	175	165	144	160	184	169	199	213
2	**Polycrystalline Quartz**	9	0	0	2	0	5	4	3	2	15	0	22	14	10	8	2	5	3	1	0
3	**Potassium Feldspars**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	**Plagioclase**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	**Lithics**	60	64	77	75	74	54	75	17	38	12	28	15	16	36	52	61	34	58	30	31
6	**Matrix**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	**Muscovite**	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
8	**Kaolinite**	0	0	1	0	1	3	2	2	0	0	3	2	0	0	0	7	5	2	2	4
9	**Iron Oxide**	35	13	61	24	18	72	42	5	44	38	113	46	39	16	13	21	7	6	7	1
10	**Quartz Overgrowth**	0	0	0	0	0	0	0	17	9	11	5	14	16	0	0	0	8	13	4	3
11	**Intergranular Porosity**	69	60	8	34	35	11	10	54	25	48	0	38	39	66	73	36	53	47	54	45
12	**Intragranular Porosity**	12	7	11	13	10	8	8	4	7	8	0	5	1	7	10	13	4	2	3	3
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	**Monocrystalline Quartz**	38.33%	52.00%	47.33%	50.67%	54.00%	49.00%	52.67%	66.00%	58.00%	55.67%	50.33%	52.67%	58.33%	55.00%	48.00%	53.33%	61.33%	56.33%	66.33%	71.00%
2	**Polycrystalline Quartz**	3.00%	0.00%	0.00%	0.67%	0.00%	1.67%	1.33%	1.00%	0.67%	5.00%	0.00%	7.33%	4.67%	3.33%	2.67%	0.67%	1.67%	1.00%	0.33%	0.00%
3	**Potassium Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	**Plagioclase**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	**Lithics**	20.00%	21.33%	25.67%	25.00%	24.67%	18.00%	25.00%	5.67%	12.67%	4.00%	9.33%	5.00%	5.33%	12.00%	17.33%	20.33%	11.33%	19.33%	10.00%	10.33%
6	**Matrix**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	**Muscovite**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.00%	0.33%	0.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
8	**Kaolinite**	0.00%	0.00%	0.33%	0.00%	0.33%	1.00%	0.67%	0.67%	0.00%	0.00%	1.00%	0.67%	0.00%	0.00%	0.00%	2.33%	1.67%	0.67%	0.67%	1.33%
9	**Iron Oxide**	11.67%	4.33%	20.33%	8.00%	6.00%	24.00%	14.00%	1.67%	14.67%	12.67%	37.67%	15.33%	13.00%	5.33%	4.33%	7.00%	2.33%	2.00%	2.33%	0.33%
10	**Quartz Overgrowth**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	5.67%	3.00%	3.67%	1.67%	4.67%	5.33%	0.00%	0.00%	0.00%	2.67%	4.33%	1.33%	1.00%
11	**Intergranular Porosity**	23.00%	20.00%	2.67%	11.33%	11.67%	3.67%	3.33%	18.00%	8.33%	16.00%	0.00%	12.67%	13.00%	22.00%	24.33%	12.00%	17.67%	15.67%	18.00%	15.00%
12	**Intragranular Porosity**	4.00%	2.33%	3.67%	4.33%	3.33%	2.67%	2.67%	1.33%	2.33%	2.67%	0.00%	1.67%	0.33%	2.33%	3.33%	4.33%	1.33%	0.67%	1.00%	1.00%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	27.00%	22.33%	6.33%	15.67%	15.00%	6.33%	6.00%	19.33%	10.67%	18.67%	0.00%	14.33%	13.33%	24.33%	27.67%	16.33%	19.00%	16.33%	19.00%	16.00%
	QFL Count	184	220	219	229	236	206	237	218	214	194	179	195	205	211	204	223	223	230	230	244
1	**Quartz**	124	156	142	154	162	152	162	201	176	182	151	180	189	175	152	162	189	172	200	213
2	**Feldspars**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	**Lithics**	60	64	77	75	74	54	75	17	38	12	28	15	16	36	52	61	34	58	30	31
1	**Quartz**	67.39%	70.91%	64.84%	67.25%	68.64%	73.79%	68.35%	92.20%	82.24%	93.81%	84.36%	92.31%	92.20%	82.94%	74.51%	72.65%	84.75%	74.78%	86.96%	87.30%
2	**Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	**Lithics**	32.61%	29.09%	35.16%	32.75%	31.36%	26.21%	31.65%	7.80%	17.76%	6.19%	15.64%	7.69%	7.80%	17.06%	25.49%	27.35%	15.25%	25.22%	13.04%	12.70%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
	Section	U305	U305	U305	U305	U305	U305	U305	U305	U401	U401	U401	U401	U401	U401	U401	U401	U401	U501-a	U501-a	U501-a
	Sample	S5	S6	S7	S8-a	S8-c	S8-d	S8-e	S9	S1	S2	S3	S4	S5	S6	S7	S8	S9	S1-a	S1-b	S2-a
1	Monocrystalline Quartz	189	142	191	151	139	112	162	116	165	169	179	191	180	159	185	185	177	212	196	190
2	Polycrystalline Quartz	5	41	5	1	2	1	0	2	3	2	27	6	8	47	5	16	4	2	5	5
3	Potassium Feldspars	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Plagioclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Lithics	21	11	44	99	65	21	57	69	51	28	11	38	25	15	15	25	64	26	31	45
6	Matrix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Muscovite	0	0	0	4	10	13	2	19	0	3	0	0	0	0	0	0	0	0	0	2
8	Kaolinite	5	0	1	9	4	0	13	13	5	9	5	1	3	1	0	6	17	12	4	17
9	Iron Oxide	8	14	1	3	63	151	6	75	11	22	16	31	20	6	3	4	0	3	0	1
10	Quartz Overgrowth	15	26	11	2	0	2	7	2	21	17	22	3	20	26	27	20	12	15	13	17
11	Intergranular Porosity	54	60	41	10	14	0	43	2	41	48	40	30	43	45	58	39	22	26	49	22
12	Intragranular Porosity	3	6	6	20	3	0	10	2	3	2	0	0	1	1	7	5	4	4	2	1
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	Monocrystalline Quartz	63.00%	47.33%	63.67%	50.33%	46.33%	37.33%	54.00%	38.67%	55.00%	56.33%	59.67%	63.67%	60.00%	53.00%	61.67%	61.67%	59.00%	70.67%	65.33%	63.33%
2	Polycrystalline Quartz	1.67%	13.67%	1.67%	0.33%	0.67%	0.33%	0.00%	0.67%	1.00%	0.67%	9.00%	2.00%	2.67%	15.67%	1.67%	5.33%	1.33%	0.67%	1.67%	1.67%
3	Potassium Feldspars	0.00%	0.00%	0.00%	0.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	Plagioclase	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	Lithics	7.00%	3.67%	14.67%	33.00%	21.67%	7.00%	19.00%	23.00%	17.00%	9.33%	3.67%	12.67%	8.33%	5.00%	5.00%	8.33%	21.33%	8.67%	10.33%	15.00%
6	Matrix	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	Muscovite	0.00%	0.00%	0.00%	1.33%	3.33%	4.33%	0.67%	6.33%	0.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.67%
8	Kaolinite	1.67%	0.00%	0.33%	3.00%	1.33%	0.00%	4.33%	4.33%	1.67%	3.00%	1.67%	0.33%	1.00%	0.33%	0.00%	2.00%	5.67%	4.00%	1.33%	5.67%
9	Iron Oxide	2.67%	4.67%	0.33%	1.00%	21.00%	50.33%	2.00%	25.00%	3.67%	7.33%	5.33%	10.33%	6.67%	2.00%	1.00%	1.33%	0.00%	1.00%	0.00%	0.33%
10	Quartz Overgrowth	5.00%	8.67%	3.67%	0.67%	0.00%	0.67%	2.33%	0.67%	7.00%	5.67%	7.33%	1.00%	6.67%	8.67%	9.00%	6.67%	4.00%	5.00%	4.33%	5.67%
11	Intergranular Porosity	18.00%	20.00%	13.67%	3.33%	4.67%	0.00%	14.33%	0.67%	13.67%	16.00%	13.33%	10.00%	14.33%	15.00%	19.33%	13.00%	7.33%	8.67%	16.33%	7.33%
12	Intragranular Porosity	1.00%	2.00%	2.00%	6.67%	1.00%	0.00%	3.33%	0.67%	1.00%	0.67%	0.00%	0.00%	0.33%	0.33%	2.33%	1.67%	1.33%	1.33%	0.67%	0.33%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	19.00%	22.00%	15.67%	10.00%	5.67%	0.00%	17.67%	1.33%	14.67%	16.67%	13.33%	10.00%	14.67%	15.33%	21.67%	14.67%	8.67%	10.00%	17.00%	7.67%
	QFL Count	215	194	240	252	206	134	219	187	219	199	217	235	213	221	205	226	245	240	232	240
1	Quartz	194	183	196	152	141	113	162	118	168	171	206	197	188	206	190	201	181	214	201	195
2	Feldspars	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Lithics	21	11	44	99	65	21	57	69	51	28	11	38	25	15	15	25	64	26	31	45
1	Quartz	90.23%	94.33%	81.67%	60.32%	68.45%	84.33%	73.97%	63.10%	76.71%	85.93%	94.93%	83.83%	88.26%	93.21%	92.68%	88.94%	73.88%	89.17%	86.64%	81.25%
2	Feldspars	0.00%	0.00%	0.00%	0.40%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	Lithics	9.77%	5.67%	18.33%	39.29%	31.55%	15.67%	26.03%	36.90%	23.29%	14.07%	5.07%	16.17%	11.74%	6.79%	7.32%	11.06%	26.12%	10.83%	13.36%	18.75%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
	Section	U501-a	U501-a	U502	U502	U502	U502	T101	T101	T101	T101	T101	T101	T101	T101	T101	T101	T101	T102	T102	T102
	Sample	S2-b	S3-a	S1	S2	S3-1	S3-2	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S1	S2	S3
1	Monocrystalline Quartz	198	130	208	217	79	59	210	155	182	94	149	205	143	221	209	219	196	142	168	193
2	Polycrystalline Quartz	2	0	2	10	1	1	2	1	1	0	2	2	0	3	1	1	0	1	23	6
3	Potassium Feldspars	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Plagioclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Lithics	26	6	4	5	5	6	10	96	42	57	54	30	101	8	23	19	22	92	13	18
6	Matrix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Muscovite	0	5	0	0	9	18	0	1	4	17	3	4	3	0	0	0	0	1	1	0
8	Kaolinite	9	13	0	3	3	0	0	1	0	0	1	0	1	2	0	0	5	19	2	16
9	Iron Oxide	9	142	2	4	203	216	33	41	32	132	58	12	46	6	24	16	42	45	34	48
10	Quartz Overgrowth	12	4	16	13	0	0	9	5	12	0	8	12	6	13	8	12	9	0	20	15
11	Intergranular Porosity	44	0	66	48	0	0	36	0	26	0	24	35	0	45	29	27	23	0	36	2
12	Intragranular Porosity	0	0	2	0	0	0	0	0	1	0	1	0	0	2	6	6	3	0	3	2
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	Monocrystalline Quartz	66.00%	43.33%	69.33%	72.33%	26.33%	19.67%	70.00%	51.67%	60.67%	31.33%	49.67%	68.33%	47.67%	73.67%	69.67%	73.00%	65.33%	47.33%	56.00%	64.33%
2	Polycrystalline Quartz	0.67%	0.00%	0.67%	3.33%	0.33%	0.33%	0.67%	0.33%	0.33%	0.00%	0.67%	0.67%	0.00%	1.00%	0.33%	0.33%	0.00%	0.33%	7.67%	2.00%
3	Potassium Feldspars	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	Plagioclase	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	Lithics	8.67%	2.00%	1.33%	1.67%	1.67%	2.00%	3.33%	32.00%	14.00%	19.00%	18.00%	10.00%	33.67%	2.67%	7.67%	6.33%	7.33%	30.67%	4.33%	6.00%
6	Matrix	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	Muscovite	0.00%	1.67%	0.00%	0.00%	3.00%	6.00%	0.00%	0.33%	1.33%	5.67%	1.00%	1.33%	1.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.33%	0.00%
8	Kaolinite	3.00%	4.33%	0.00%	1.00%	1.00%	0.00%	0.00%	0.33%	0.00%	0.00%	0.33%	0.00%	0.33%	0.67%	0.00%	0.00%	1.67%	6.33%	0.67%	5.33%
9	Iron Oxide	3.00%	47.33%	0.67%	1.33%	67.67%	72.00%	11.00%	13.67%	10.67%	44.00%	19.33%	4.00%	15.33%	2.00%	8.00%	5.33%	14.00%	15.00%	11.33%	16.00%
10	Quartz Overgrowth	4.00%	1.33%	5.33%	4.33%	0.00%	0.00%	3.00%	1.67%	4.00%	0.00%	2.67%	4.00%	2.00%	4.33%	2.67%	4.00%	3.00%	0.00%	6.67%	5.00%
11	Intergranular Porosity	14.67%	0.00%	22.00%	16.00%	0.00%	0.00%	12.00%	0.00%	8.67%	0.00%	8.00%	11.67%	0.00%	15.00%	9.67%	9.00%	7.67%	0.00%	12.00%	0.67%
12	Intragranular Porosity	0.00%	0.00%	0.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.00%	0.33%	0.00%	0.00%	0.67%	2.00%	2.00%	1.00%	0.00%	1.00%	0.67%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	14.67%	0.00%	22.67%	16.00%	0.00%	0.00%	12.00%	0.00%	9.00%	0.00%	8.33%	11.67%	0.00%	15.67%	11.67%	11.00%	8.67%	0.00%	13.00%	1.33%
	QFL Count	226	136	214	232	85	66	222	252	225	151	205	237	244	232	233	239	218	235	204	217
1	Quartz	200	130	210	227	80	60	212	156	183	94	151	207	143	224	210	220	196	143	191	199
2	Feldspars	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Lithics	26	6	4	5	5	6	10	96	42	57	54	30	101	8	23	19	22	92	13	18
1	Quartz	88.50%	95.59%	98.13%	97.84%	94.12%	90.91%	95.50%	61.90%	81.33%	62.25%	73.66%	87.34%	58.61%	96.55%	90.13%	92.05%	89.91%	60.85%	93.63%	91.71%
2	Feldspars	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	Lithics	11.50%	4.41%	1.87%	2.16%	5.88%	9.09%	4.50%	38.10%	18.67%	37.75%	26.34%	12.66%	41.39%	3.45%	9.87%	7.95%	10.09%	39.15%	6.37%	8.29%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

#	Count	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141
	Section	T103-b	T103b	T103b	T103b	T103b	T104	T104	T104	T104	T104	T105	T105	T105	T105	T105	T105	T105	T105	T105	T105	T105
	Sample	S1	S2	S4	S5	S6	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S6	S7	S8-1	S8-2	S8-3	S8-4
1	**Monocrystalline Quartz**	194	170	166	198	186	179	190	169	149	208	210	167	216	229	226	205	215	125	114	211	107
2	**Polycrystalline Quartz**	1	5	24	2	1	4	2	5	0	0	0	0	0	0	0	7	7	0	1	0	0
3	**Potassium Feldspars**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	1	0	0	0	0
4	**Plagioclase**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	**Lithics**	10	7	16	12	13	14	18	17	25	10	3	109	5	16	0	3	3	79	5	44	17
6	**Matrix**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	**Muscovite**	0	0	0	0	0	0	0	0	2	0	0	3	0	3	0	0	0	26	9	7	1
8	**Kaolinite**	2	0	0	2	2	2	4	17	7	0	0	1	0	0	1	0	0	3	0	2	0
9	**Iron Oxide**	39	97	55	38	63	39	42	40	103	42	11	19	6	29	7	22	9	67	166	9	169
10	**Quartz Overgrowth**	17	13	18	7	5	18	18	17	11	10	21	1	20	10	18	10	10	0	5	5	0
11	**Intergranular Porosity**	37	8	18	41	16	41	24	28	3	29	55	0	53	9	48	49	55	0	0	14	6
12	**Intragranular Porosity**	0	0	3	0	14	3	1	7	0	1	0	0	0	4	0	0	0	0	0	8	0
	Count	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1	**Monocrystalline Quartz**	64.67%	56.67%	55.33%	66.00%	62.00%	59.67%	63.33%	56.33%	49.67%	69.33%	70.00%	55.67%	72.00%	76.33%	75.33%	68.33%	71.67%	41.67%	38.00%	70.33%	35.67%
2	**Polycrystalline Quartz**	0.33%	1.67%	8.00%	0.67%	0.33%	1.33%	0.67%	1.67%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%	2.33%	0.00%	0.33%	0.00%	0.00%
3	**Potassium Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.33%	0.33%	0.00%	0.00%	0.00%	0.00%
4	**Plagioclase**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	**Lithics**	3.33%	2.33%	5.33%	4.00%	4.33%	4.67%	6.00%	5.67%	8.33%	3.33%	1.00%	36.33%	1.67%	5.33%	0.00%	1.00%	1.00%	26.33%	1.67%	14.67%	5.67%
6	**Matrix**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	**Muscovite**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.67%	0.00%	0.00%	1.00%	0.00%	1.00%	0.00%	0.00%	0.00%	8.67%	3.00%	2.33%	0.33%
8	**Kaolinite**	0.67%	0.00%	0.00%	0.67%	0.67%	0.67%	1.33%	5.67%	2.33%	0.00%	0.00%	0.33%	0.00%	0.00%	0.33%	0.00%	0.00%	1.00%	0.00%	0.67%	0.00%
9	**Iron Oxide**	13.00%	32.33%	18.33%	12.67%	21.00%	13.00%	14.00%	13.33%	34.33%	14.00%	3.67%	6.33%	2.00%	9.67%	2.33%	7.33%	3.00%	22.33%	55.33%	3.00%	56.33%
10	**Quartz Overgrowth**	5.67%	4.33%	6.00%	2.33%	1.67%	6.00%	6.00%	5.67%	3.67%	3.33%	7.00%	0.33%	6.67%	3.33%	6.00%	3.33%	3.33%	0.00%	1.67%	1.67%	0.00%
11	**Intergranular Porosity**	12.33%	2.67%	6.00%	13.67%	5.33%	13.67%	8.00%	9.33%	1.00%	9.67%	18.33%	0.00%	17.67%	3.00%	16.00%	16.33%	18.33%	0.00%	0.00%	4.67%	2.00%
12	**Intragranular Porosity**	0.00%	0.00%	1.00%	0.00%	4.67%	1.00%	0.33%	2.33%	0.00%	0.33%	0.00%	0.00%	0.00%	1.33%	0.00%	0.00%	0.00%	0.00%	0.00%	2.67%	0.00%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	Total Porosity	12.33%	2.67%	7.00%	13.67%	10.00%	14.67%	8.33%	11.67%	1.00%	10.00%	18.33%	0.00%	17.67%	4.33%	16.00%	16.33%	18.33%	0.00%	0.00%	7.33%	2.00%
	QFL Count	205	182	206	212	200	197	211	191	174	218	213	276	221	245	226	219	226	204	120	255	124
1	**Quartz**	195	175	190	200	187	183	192	174	149	208	210	167	216	229	226	212	222	125	115	211	107
2	**Feldspars**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	1	0	0	0	0
3	**Lithics**	10	7	16	12	13	14	18	17	25	10	3	109	5	16	0	3	3	79	5	44	17
1	**Quartz**	95.12%	96.15%	92.23%	94.34%	93.50%	92.89%	91.00%	91.10%	85.63%	95.41%	98.59%	60.51%	97.74%	93.47%	100.00%	96.80%	98.23%	61.27%	95.83%	82.75%	86.29%
2	**Feldspars**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.47%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.83%	0.44%	0.00%	0.00%	0.00%	0.00%
3	**Lithics**	4.88%	3.85%	7.77%	5.66%	6.50%	7.11%	8.53%	8.90%	14.37%	4.59%	1.41%	39.49%	2.26%	6.53%	0.00%	1.37%	1.33%	38.73%	4.17%	17.25%	13.71%
	Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

LITHOSTRATIGRAPHIC INTERPRETATIONS

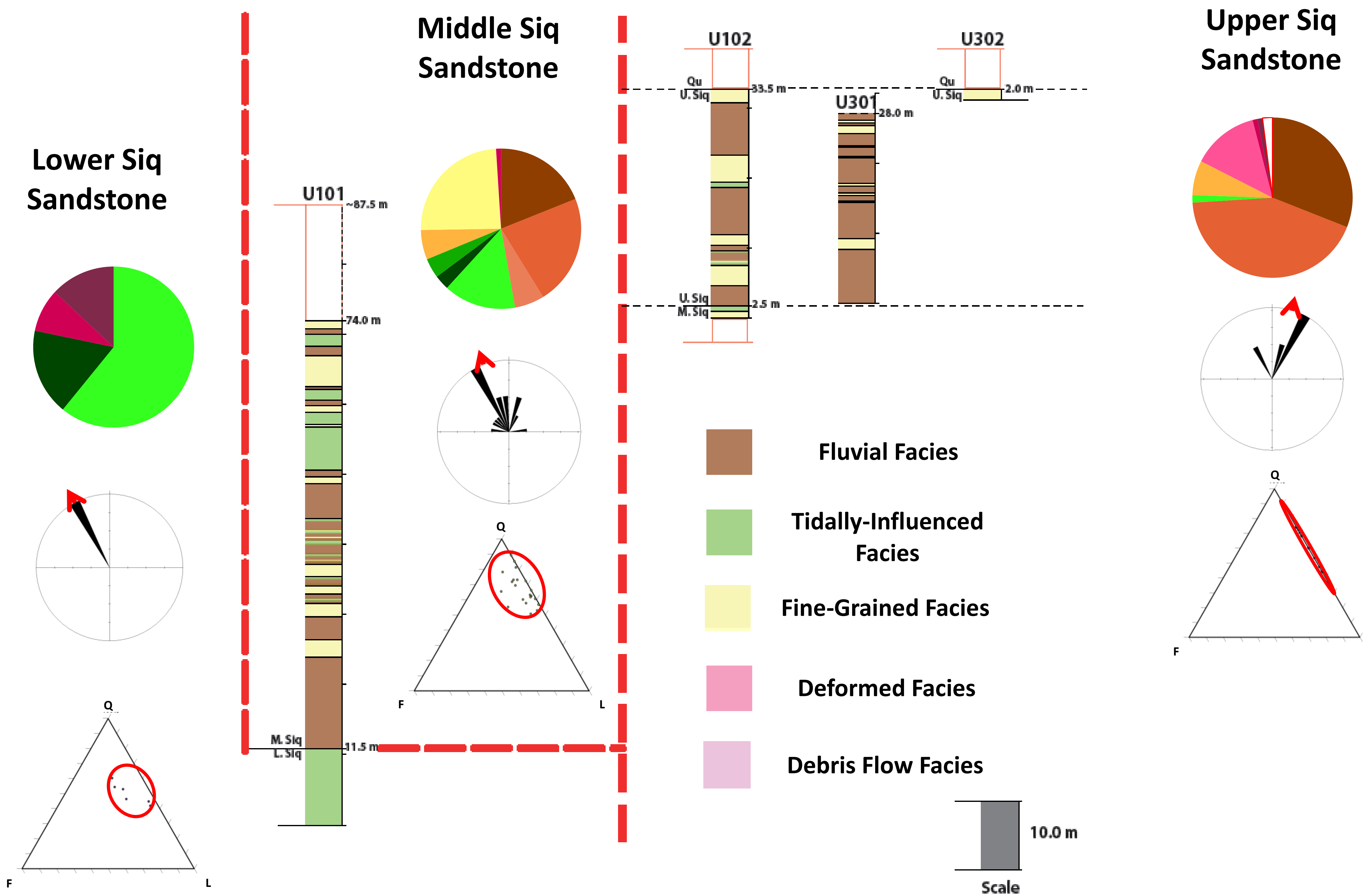


Figure 6: Summary display of datasets collected from the Siq Sandstone units in the Al Ula study area, including measured sections displaying facies associations, in addition to QFL (100%) ternary plots, paleocurrent direction rose diagrams and facies distribution pie charts for each of the Siq Sandstone sub units.

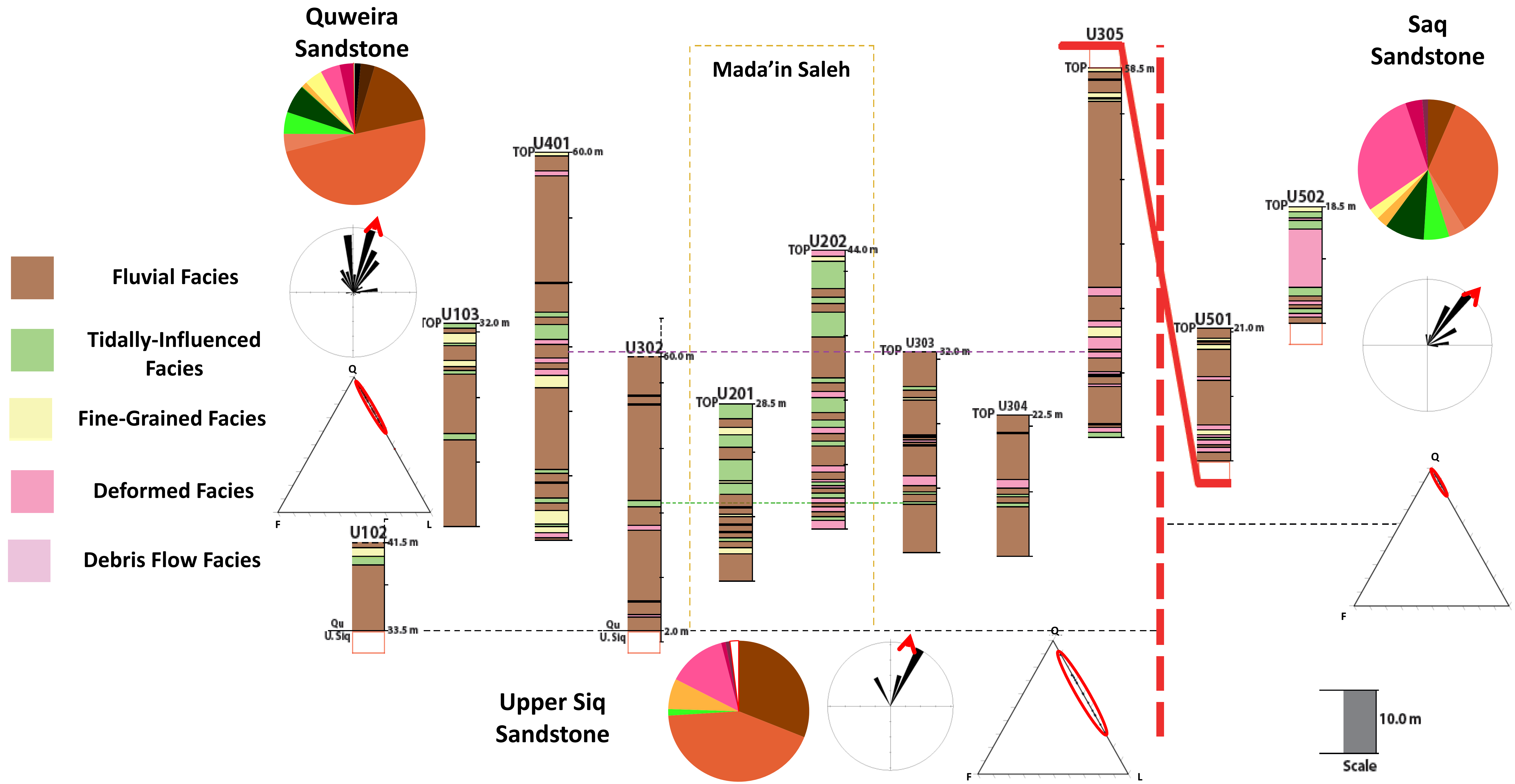


Figure 7: Summary display of datasets collected from the Upper Siq, Quweira and Saq Sandstone units in the Al Ula study area, including measured sections displaying facies associations, in addition facies distribution pie charts, paleocurrent direction rose diagrams and QFL (100%) ternary plots for each of these units.

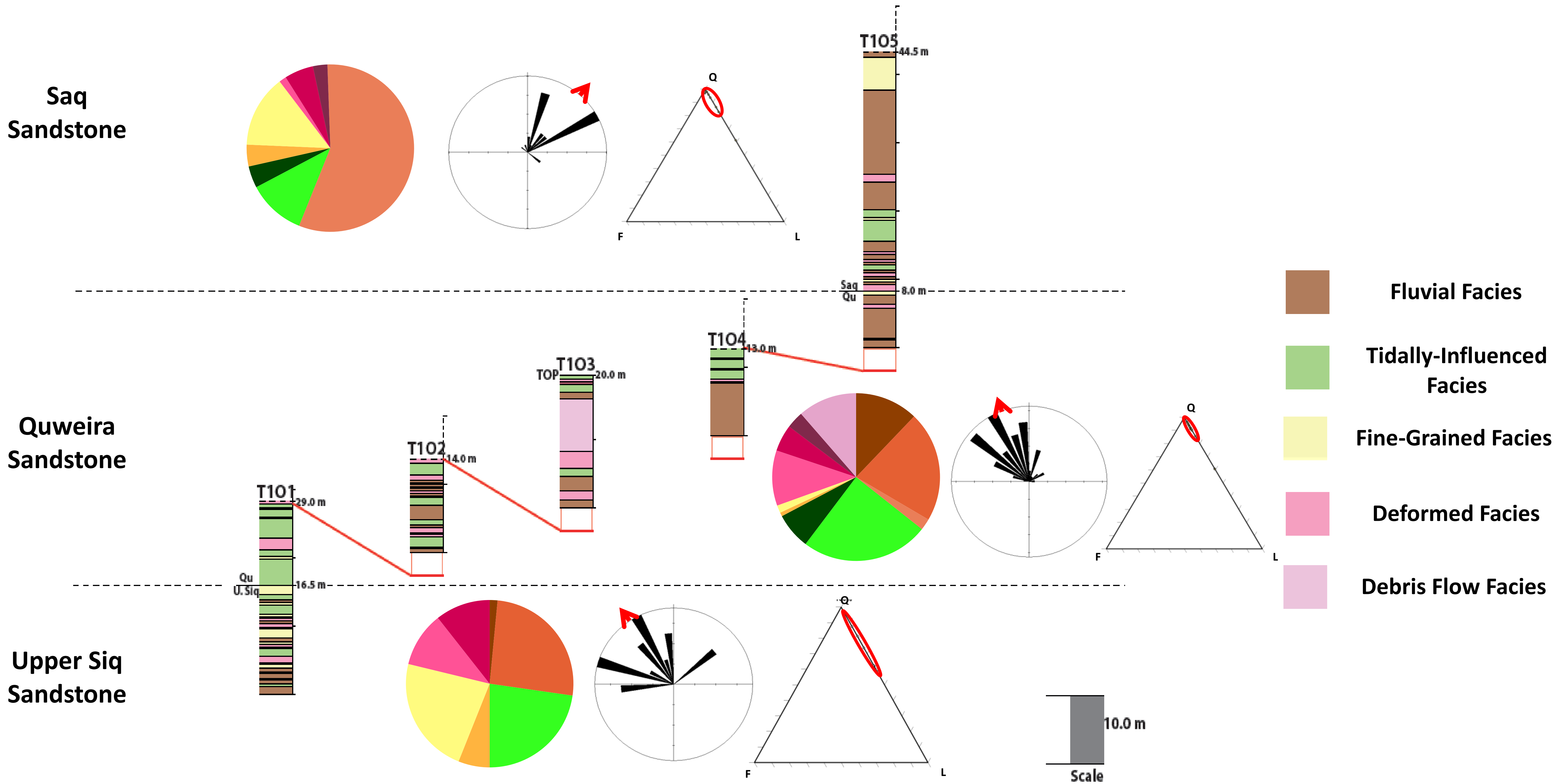


Figure 8: Summary display of datasets collected from the Upper Siq, Quweira and Saq Sandstone units in the Tabuk study area, including measured sections displaying facies associations, in addition facies distribution pie charts, paleocurrent direction rose diagrams and QFL (100%) ternary plots for each of these units.

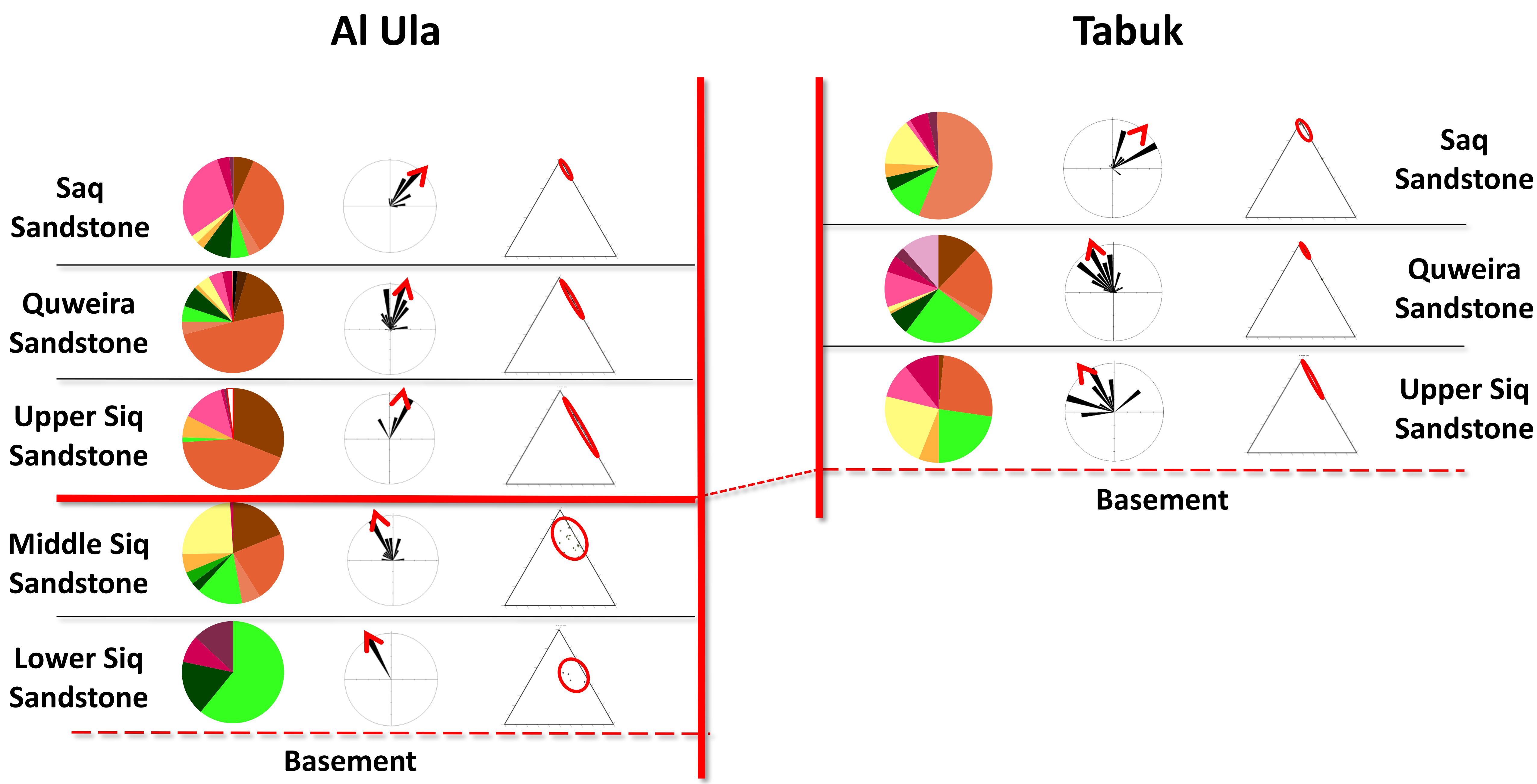


Figure 9: Summary of the different lithostratigraphic units studied the Al Ula and Tabuk areas with a correlation between equivalent lithostratigraphic units.

VITAE

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Abdullah Wahbi is a clastic sedimentologist working in the Reservoir Characterization Department in Saudi Aramco in Dhahran, Saudi Arabia. After completing high school, He was awarded a full scholarship through the Saudi Aramco College Degree Program for Non-Employees (CDPNE). He started his Bachelor's degree program in Geology at Louisiana State University in Baton Rouge, Louisiana in the United States of America in August 2005. Upon his graduation in August 2009, he started his career in Saudi Aramco, holding various positions in the company as a geosteering geologist, wellsite geologist and reservoir geologist. In July 2011, Abdullah was nominated to become a member in the Saudi Aramco Exploration's Specialist Development Program (SDP), a program designed to support the technical development and specialization of young talents in the company. With clastic sedimentology as his selected specialty, he develops facies descriptions and conceptual lithostratigraphic subsurface models relying primarily on core descriptions that are ultimately utilized in fully-integrated reservoir models. In addition to his professional career at Saudi Aramco, Abdullah Wahbi started his part-time graduate program in February 2010 at King Fahd University of Petroleum and Minerals (KFUPM), studying for his Master's degree in

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